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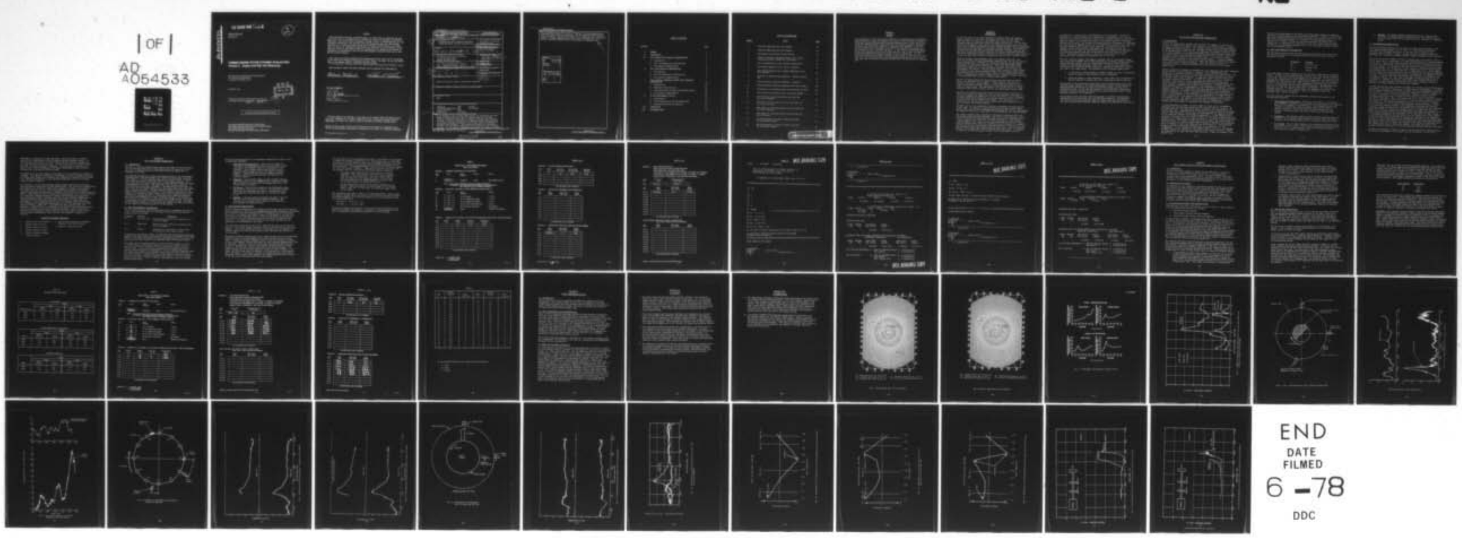

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AFAPL-TR-76-81
Volume II

TURBINE ENGINE ROTOR DYNAMIC EVALUATION
Volume II. Engine and Rig Test Balancing

MECHANICAL TECHNOLOGY INCORPORATED
968 ALBANY-SHAKER ROAD
LATHAM, NEW YORK 12110

JANUARY 1978

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TECHNICAL REPORT AFAPL-TR-76-81, Volume II
Final Report for Period ~~January 1975 – December 1975~~
4/1/76 – 11/1/77

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This program was initiated with FY 75 Aero-Propulsion Laboratory Director's Funds.

This technical report has been reviewed and is approved for publication.

Robert Millard　　　　William A Tioka

FOR THE COMMANDER

H I Bush

H. I. BUSH
Deputy Director
Turbine Engine Division

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As an extension of the original AFAPL Contract for determining the rotor-dynamics characteristics of eight jet engines within the Air Force inventory, Mechanical Technology Incorporated performed balancing demonstrations to show the applicability of combining dynamic characteristics and advanced balancing techniques to effectively reduce the vibration of production type machinery. Trim balancing procedures were performed on the TF30, TF41 and F100 jet engines which are currently in use on military aircraft. A very sensitive high-speed experimental test apparatus called over

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

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SECTION I

SUMMARY

As an extension of the original AFAPL Contract for determining the rotordynamics characteristics of eight jet engines within the Air Force inventory, Mechanical Technology Incorporated performed balancing demonstrations to show the applicability of combining dynamic characteristics and advanced balancing techniques to effectively reduce the vibration of production type machinery. Trim balancing procedures were performed on the TF30, TF41 and F100 jet engines which are currently in use on military aircraft. A very sensitive high-speed experimental test apparatus called the "Rub Rig" was also used to show the benefits of multiplane-multispeed balancing using influence coefficients. All the balancing operations were highly successful, and showed the potential for using this type of balancing system to increase manpower productivity, reduce operating cost, and to provide a precision balanced rotor for production or laboratory use.

SECTION II
INTRODUCTION

In the first part of the Turbine Engine Rotor Dynamics Evaluation program, Volume I, eight of the Air Force jet engines (T56, J57, J79, J85, TF30, TF33, TF39, and TF41) were analyzed to determine rotor system critical speeds, unbalance response, blade loss effects and maneuver deflections. In this effort, the effects of dampers, thrust loads, rotor interactions with supports and other rotors, and balancing requirements were not analyzed in depth, but were noted where applicable in the description of the engine's dynamic behavior. The analytical critical speed and mode shape calculations identified locations along the axis of each rotor system which would be effective for in-place, high-speed balancing. The efforts discussed in Volume II describe how the application of these analytical studies and high-speed balancing techniques are used to reduce vibration levels.

For this contract, three different types of jet engines (TF30, TF41, and F100) and an AFAPL high-speed experimental compressor seal rub rig were used for these balancing tests. The TF30 is a two-spool, augmented turbofan engine manufactured by Pratt and Whitney Aircraft Division of United Technologies Corporation of East Hartford, Connecticut. Over 6,000 TF30 engines of all versions have been built to power the General Dynamics F-111F Aircraft and the Grumman F-14A Aircraft. The low-pressure spool consists of three titanium fan stages and six titanium compressor stages, with an integral construction. This nine-stage spool is driven through a shaft by three low-pressure turbine stages. The high-pressure spool consists of seven compressor stages constructed of a nickel-base alloy, driven by a single-stage turbine.

The TF41 is manufactured by the Detroit Diesel Allison Division of General Motors, and powers the LTV A-7 series of attack aircraft. The TF41 is a two-spool, low bypass turbofan engine. A three-stage titanium fan and two-stage, low-pressure compressor section are driven through a shaft by two low-pressure turbine stages. The high-pressure rotor system consists of eleven compressor stages driven through a shaft by two high-pressure turbine stages.

The F100 is an advanced technology turbofan engine designed specifically to power current generation fighters for the Air Force and Navy. The engine is a two-spool, augmented fan manufactured by Pratt and Whitney Aircraft Division of United Technologies Corporation, and was developed at the Pratt and Whitney Florida Research and Development Center (FRDC). The F100 engine is in production, with current applications including the McDonald Douglas F15 and General Dynamics F16 advanced fighters.

The AFAPL rub rig is an experimental facility to determine the characteristics of seal rubs. It consists of a motor driven speed-increaser gearbox, which drives a shaft with a double diaphragm coupling on each end to accept misalignment. This shaft is attached to a large disk for the experimental seal rub evaluations.

Two computer programs owned by Mechanical Technology Incorporated (MTI) were used during these balancing experiments. The first of these programs is called CAD 10, and permits the multiplane-multispeed balancing of rotating machinery. It may be used in field, test cell, or factory applications. This program computes magnitude and location of the correction weights required to balance a rigid or flexible rotor, either in a balancing stand or on-site. The analysis involves the use of a least-squares influence coefficient procedure to calculate the correction weights from measured rotor vibration data. Up to 20 vibration sensors, 5 balancing speeds, and 10 balancing planes may be used if required. In addition, all types of sensors (strain, force, displacement, velocity, acceleration, or other types) are compatible with this program. The method employed is to first determine rotor sensitivity to unbalance by spin testing. This spin test consists of placing a known trial unbalance weight in each balance plane of interest to determine the effect of this known weight on the dynamic behavior of the rotor. The procedure includes provision to measure and compensate for electrical and magnetic runout, and for mechanical eccentricities. Once these have been measured and recorded by the computer, a technician can direct the computer to read the amplitude, phase angle, and the speed at which the readings are to be taken for each balance plane. The computer then determines the correction weights which must be applied for effective balance of the rotor. Subsequent trim balancing of the rotor will utilize this stored sensitivity data throughout the operating life of the rotor.

With the correction weight requirements available, CAD 12, the second program used, will select weights from a given inventory of correction weights available and provide the operator with the optimum distribution of these correction weights in every balancing plane on the rotor. It also has the capability of calculating the classes of weights needed in a production inventory to balance any rotor of the same design. The program has two functional capabilities:

1. It calculates a minimum number of weight classes and their corresponding values to correct a certain model rotor or workpiece.

2. Given the amount of rotor unbalance, it will select the circumferential pattern required to balance the rotor using these inventory weights.

The second of these functional capabilities can be performed with either user-supplied weight classes or with calculated weight classes, thereby making the program equally applicable to custom, one-of-a-kind rotors, as well as to production rotors. It also has the capability of automatically distributing multiple correction weights and taking into account previously filled circumferential locations for corrections.

The following report sections have been grouped to describe each balancing demonstration on a particular piece of high-speed machinery. Information on the specific balancing operation, number of planes used, sensors available, the tools used, and the resultant vibration levels are given within each section.

SECTION III

TF30 ENGINE TRIM BALANCING DEMONSTRATION

A. Introduction

Current Air Force policy requires that aircraft jet engines, at specific intervals, be removed from service and returned to an overhaul depot to undergo an engine teardown and rebuild. The primary criteria used for removing engines is maximum allowable operating time. Maximum allowable operating time, defined as the maximum time in hours that a jet engine may be retained in service without a major overhaul, is an engineering/maintenance administrative removal used to prevent engines from reaching high operating hours or to prevent their remaining in-service beyond specific calendar times. For in-service engines, maximum time is specified in the engine overhaul manuals. Initially, maximum operating time is related to safety of flight and experience gained from engine tests during weapon system development. Once the engine is placed in operational service, actuarial forecasting is used to define future engine removal rates.

Engines received for overhaul at Oklahoma City are completely torn down, inspected, and all defective parts repaired or replaced. Rotor subassemblies and assemblies are low-speed balanced according to manufacturer's instructions. The re-assembled engine is then put on the stand and engine performance is tested. At the same time, engine vibration, as measured by three velocity sensors on the engine casing, is monitored. If either the sensor located in a forward position on the engine or at the engine mid-span indicates steady-state vibrations above 3.2 mils (double amplitude) anywhere in the speed range, the engine becomes a candidate for in-place trim balancing - provided that the vibrational frequency is predominantly at the low-pressure compressor rotational frequency (N_1), and the steady-state vibration amplitude did not exceed 5 mils (double amplitude). If either the rear-mounted sensor at the low-pressure turbine indicates above limits vibration, or if the monitored vibration at any sensor is predominantly at the frequency corresponding to the high-pressure rotor frequency (N_2), the engine is rejected and goes back to what is known as the "penalty line". The engine is then partially disassembled and selected rotating components sent back to the rework shop for rebalancing, or disassembly with interchange of components and subsequent rebalancing.

If trim balancing is in order, a trial weight is placed in the low-pressure compressor and the amplitude response at the selected speed is recorded. In two additional runs, the same trial weight is moved in the same plane by 120 degrees each time. Amplitudes from the original run and the three trial weight runs are then plotted on a polar plot, and the magnitude and angular location of the correction weights are determined graphically. If the vibration data recorded is accurate, the locus points (circle) of each trial weight vector will intersect at a single point, as shown in Figure 1, to provide a unique correction weight solution. When there is some scatter in the data, the point closest to all three vectors is chosen by graphically drawing the smallest circle possible which is tangent to the trial weight vectors (see Figure 2). Trim balancing weights can then be installed, provided they do not exceed 4.0 oz.-in. in magnitude. If the calculated trim weights exceed 4.0 oz.-in., the maximum allowable amount will probably be installed and the engine re-tested. Should the engine still not meet vibration specifications, it must be returned to the penalty line.

The trim balance operation on the TF30, as on most other engines, is generally limited to a single plane on the low-pressure compressor. Actually, on the TF30, two closely spaced balancing planes are available, but typically only one is used. There are two possible reasons: 1) current trim balancing methods make it impractical to conduct a balancing correction operation distributed over two planes; and, 2) manufacturer's limitations on the total vector sum of weights attached in the low-speed compressor are too low to necessitate weight application in two adjacent planes.

B. Test Instrumentation Configuration

The TF30 engine used for this test was mounted at the inlet and turbine cases. The standard equipment for recording vibration were three velocity pickups mounted as follows:

Pickup No.	Location
No. 1	Fan Inlet Case
No. 2	Diffuser Case
No. 3	Turbine

The normal engine running configuration does not have a once-per-rev tachometer signal. During the trim balancing test a special one tooth tach was installed in the inlet case nose cone and was geared to the front hub. The initial tests required the installation of trial weights which meant that this tach had to be disengaged and then reinstalled. After several failures at the trim balancing effort, it was realized that the tooth engagement of this tach gear was very critical for obtaining accurate phase angle information. The backlash in the gears was so large that the one tooth could be installed ± 30° from the reference position. To avoid this problem, the compressor was spun by hand afterward which took up the backlash. Then, the location of the tach reference point could be repeated.

The three vibration signals and tha tachometer reference were input to the following MTI equipment:

1. <u>Dual-Channel Tracking Filter</u> - Using the tach signal as a reference, this equipment can select, from an overall vibration signal, the component which is the frequency of the reference. This equipment selects and isolates the synchronous vibration signal which is the result of inherent unbalance. Since there were only two channels and four pickups, a switching device was used to process all the available signals.

2. <u>Phasemeter</u> - The reference signal and one filtered vibration signal are patched to the phasemeter which computes the phase angle between the reference and the maximum amplitude of the filtered vibration signal.

3. <u>X-Y Plotter</u> - The DC output signals of the Dual-Channel Tracking Filter are applied to the plotter. One filtered vibration signal and the tach signal are used to instantaneously plot the synchronous vibration amplitude as a function of engine R.P.M.

4. Terminal - A portable computer terminal was used to link the test site with the computerized balancing programs. The terminal has an acoustic coupler which can be connected to any telephone for immediate access.

C. Trim Balancing Demonstration

The trim balancing demonstration took place at Tinker Air Force Base on the TF30 engine between October 4 and 7, 1976. For this purpose, MTI-owned electronic data equipment was set up in the test cell in parallel with equipment made available by Tinker. Balance correction weight calculations were made via a telephone-connected portable computer terminal in the test cell.

The first step in any attempt to balance a machine must be an effort to gain, either analytically or experimentally, some understanding of the dynamic response of the rotor. Rotor system critical speeds and the associated mode shapes that the rotor will assume will greatly help in the selection of appropriate balance correction planes. In the case of the TF30, where the balance correction plane is pre-determined, such information is still needed to help distinguish whether the unbalance source is in either the low- or high-speed rotor. As an example, Figure 3 shows the expected responses from an engine where the expected unbalance is in the low-speed compressor and, hence, correctable by trim balancing (Class 1 in Figure 3) and from one other engine where the unbalance is probably in the low-pressure turbine, and, thus, not correctable by trim balancing (Class II in Figure 3). Similar calculations made by MTI under W-PAFB contract for a number of selected engines, of which the TF30 was one, provided a basis for evaluation of engine response and balance improvements.

Two TF30 engines were made available at Tinker for at least partial MTI balancing experiments. The first engine was a P-7 model and the second engine a P-3 model. The P-7 engine exhibited a vibrational pattern that was predominently caused by the high rotor. Since there is no access for high-rotor correction weights, the P-7 was not considered to be trim balanceable. Despite this fact and the subsequent shipping of the P-7 engine to the penalty line, some valuable conclusions were made. First, two repeat runs in the "as-is" condition revealed that rotor repeatability may be sufficient if similar power acceleration rates are adhered to. The second observation was that a trial weight of 12 grams, which is one-half of the allowable trim balancing correction weight, attached at an arbitrary angular location in the compressor balancing plane caused a sufficient change in amplitude at the forward sensor location (at the compressor inlet) to be used for future trial weight values. The amplitude peak above 6000 R.P.M. N_1 speed recorded by the compressor inlet sensor was affected by the trial weight placement in the same manner as the amplitudes at higher speeds. If the observed amplitude peak had been due to the turbine mode, less response should have been noted for changes in the balance condition of the compressor. At least a partial explanation of the anomaly was provided when the second engine was tested. The second engine (P-3) also exhibited a very pronounced amplitude peak above 6000 R.P.M. N_1 speed, which showed a very marked decrease when one of the forward mount support struts was removed. This meant that some of the observed vibration was caused by the test hardward inducing loads into the engine.

Besides the experimental removal of one of the forward facility support mounts, two balancing experiments were conducted on the P-3 engine. In the first experiment, a 6-gram trial weight was used. The trial weight of 6-grams proved to be insufficient to give the desired minimum response change. For the original condition and the trial weight run, the vibration responses at the inlet case were nearly the same. A trial weight should be selected which provides a 50 percent change in response. If the change in response is too small, errors from instrumentation and engine repeatability will adversely influence the calculated correction weight.

Consequently, a new trial weight run was made with an increased trial weight of 18 grams. This data was sufficient to determine a correction weight based upon the single trial weight run, showing a very significant reduction of the maximum rotor vibration amplitudes for the low-speed compressor over the full-speed range as shown in Figure 4.

The application of the semi-automated turbine engine trim balance procedures using influence coefficients was thus demonstrated. The trim balance demonstration was conducted on a TF30 P-3 engine which originally exceeded the permissible tech order vibration limits. After trim balancing the engine, the maximum vibration amplitude was reduced by 67 percent-- well below the acceptable operating limits. The success of this prototype system demonstration led to the definition of a completely automated system for engine trim balancing and diagnostics. This system will directly interface with and utilize available capabilities of existing automated engine test equipment (Pacer-Comet II) established for performance. It is of significance to note that although these technologies were developed and demonstrated independently, they will complement each other toward achieving a common goal of increased and more efficient test cell operation. Listed below is a comparison of the present trim balancing procedure with that obtainable from using a computerized method. Most of these steps require that the engine be lowered from the test cell mount location and the front partially disassembled, which requires approximately 45 minutes to one hour.

BALANCING PROCEDURE COMPARISON

1. Install tach & run "as-is":	1. Turn on optic sensor-no disassembly required - run "as-is" survey
2. Install trial wt at 0°	2. Install correction weights
3. Install trial wt at 120°	
4. Install trial wt at 240°	
5. Install correction weight - Trial & error	

SECTION IV

TF41 TRIM BALANCING DEMONSTRATION

A. Introduction

The TF41 is a military turbofan engine used in the Vought A-7 attack aircraft. The trim balancing demonstration was performed while the engine was in the test cell at Wright-Patterson Air Force Base the week of August 31st to September 3rd of 1976.

As background information to assist the balancing operation, the rotordynamics characteristics of the low-pressure rotor system had already been calculated (see Volume I). From this analysis there are two critical speeds of the low rotor system which must be traversed during normal engine operation. The first occurs low in the speed range and is a turbine-excited resonance, showing the predominent motion there. The upper mode, near top speed, shows the cantilevered fan as the major contributor. The mode shape indicates that the front of the fan is furthest displaced from the engine center line, which would make it the most sensitive. The Test Instruction Sheets (TIS) issued by the engine manufacturer allow the addition of trim correction weights on the front flange of the overhung fan stage. Based on the critical speed analysis, this location is an optimum position for correcting fan/low compressor unbalance and probably was designed on the basis of similar analyses. The TIS does not allow for any trim corrections in the turbine even though the last rotor stage is accessible and an ideal location based on the previous studies. The AFAPL Project Engineer decided not to violate the TF41 engine tech orders and limited the TF41 engine trim balancing study to the fan section.

B. Test Instrumentation Configuration

The TF41 engine used for this test was mounted at the intermediate and turbine cases. The standard equipment for recording vibration were three velocity pickups mounted as follows:

Pickup No.	Location	Orientation
No. 1	Fan Inlet Case	Records vertical vibration as mounted on the top of the engine.
No. 2	Burner Rail	Records vertical vibration as mounted on the top of the engine.
No. 3	Turbine	Records vertical vibration as mounted near the bottom on a main support strut.

In addition to the standard sensors, an additional horizontal velocity probe was mounted on the engine case in line with the front mount to examine for test stand effects. This sensor was mounted to record horizontal motion of the case at the mounts which are more flexible in the horizontal than the vertical direction.

The normal engine configuration does not leave any means available to record a once-per-revolution tachometer signal for the low rotor system. Since a rotor reference point is required, the front spinner was painted half black and half white. A photo-optic probe was mounted on the engine case with a specially designed bracket at approximately 4 o'clock (forward looking aft) with the light source pointed at the spinner. During slow roll tests, the photo-optic probe recorded a voltage shift during the transition from black to white which then provided a reference tachometer signal keyed to a specific angular location on the rotor. Figure 5 shows the instrumentation setup for the TF41 Balancing Experiments.

The four vibration signals and the tachometer reference were input to the following MTI equipment:

1. Dual-Channel Tracking Filter - Using the tach signal as a reference, this equipment can select, from an overall vibration signal, the component which is the frequency of the reference. This equipment selects and isolates the synchronous vibration signal which is the result of inherent unbalance. Since there were only two channels and four pickups, a switching device was used to process all the available signals.

2. Phasemeter - The reference signal and one filtered vibration signal are patched to the phasemeter which computes the phase angle between the reference and the maximum amplitude of the filtered vibration signal.

3. X-Y Plotter - The DC output signals of the Dual-Channel Tracking Filter are applied to the plotter. One filtered vibration signal and the tach signal are used to instantaneously plot the synchronous vibration amplitude as a function of engine R.P.M.

4. Terminal - A portable computer terminal was used to link the test site with the computerized balancing programs. The terminal has an acoustic coupler which can be connected to any telephone for immediate access.

C. Trim Balancing Demonstration

The first speed accelerations of the engine were performed very slowly (approximately 2 minutes) to check out the instrumentation and the condition of the signals. The tachometer signal was producing erratic readings and had to be corrected. The paint on the spinner had flaked off due to a combination of the heat from anti-icing air and centrifugal loads. The paint was completely removed and replaced with a strip of high-gain reflective tape which was applied with a super glue. This modification corrected the tach signal problems and was acceptable for the remainder of the tests.

The synchronous vibration for the "as-is" condition was very low, as shown in Figure 6. Of the four pickups available, only the two shown had any noticeable response. The turbine pickup does seem to show response to the apparent low turbine resonance at 3400 N_1 R.P.M., which is near the analytical prediction for this mode.

Because the vibration response was so low, trim balancing could not be performed, especially since it was anticipated that an effect would only be near high speed. A weight was applied (unknown to MTI) to the front spinner to provide us with a new baseline response from which the trim balancing demonstration could be performed. Ideally, it was anticipated that the balancing program would, in effect, determine the location of the unknown implanted weight, counterbalance it, and bring the response back down to the low levels again. The engine response for the two most sensitive pickups is shown in Figure 7. As shown, the only pickup which is sensitive to fan unbalance is in the opposite end of the engine - the turbine! Based on the analytical mode shapes (which admittedly do not include case response), the maximum deflection is at the tip of the fan, and the fan case should see some response.

The next phase of the test program was to apply a trial weight to the spinner to obtain the influence coefficients, or, rotor sensitivity. At this time, we found out that the implanted weight was the maximum allowable trim weight which could be applied to the spinner without exceeding the engine test instruction sheets. The implanted weight of 26.27 g at 110° had to be revealed. Its location is shown in Figure 8. There are two choices as to how to use the available data for verifying the balancing program's capability.

1. The larger engine response data can be used as an "initial condition". The trial weight run would be the low response from the very first engine run. The trial weight would be equal and opposite to the implanted weight. In this case, the calculated correction weight should be extremely close to the trial weight, but placed 180° from it.

2. The low response data would be the initial condition and the implanted unbalance would be the trial weight with its associated response run. In this case, the correction weight should be very small.

Both approaches were used to check out the balancing system. Table I shows the computer program input, and Table II, the calculated correction weights. For summary purposes, the correction weights for the two procedures listed above are provided here.

Procedure 1 - 26.04 g at - 75°

Procedure 2 - 2.37 g at -168°

The results compare very favorably to the logical results anticipated, and provide an extremely high degree of confidence for the application of this type of computerized trim balancing procedure to the TF41 engine.

TABLE I

MULTIPLANE – MULTISPEED BALANCING
INPUT DATA SHEET

SECTION A – COMMANDS FOR CONTROL OF CALCULATION

LINE NO.	DATA	INPUT REQUEST	OPTION	MEANS
A1	NEW	COMMAND	"NEW"	GIVE COMPLETE INPUT

NOTE: A1 WILL ALSO BE REQUESTED AFTER CALCULATIONS ARE COMPLETED.
THE COMMAND: "REPT" MEANS SECTION B IS BYPASSED IN A NEW CALCULATION
"STOP" MEANS THE USE OF THE PROGRAM IS COMPLETE.

SECTION B – SETUP DATA (USE ONLY IF "NEW" COMMAND IS GIVEN ON LINE A1)

LINE NO.	DATA	INPUT REQUEST	RANGE
B1	1	NO. OF SENSORS	(1 TO 20)
B2	1	NO. OF CORRECTION PLANES	(1 TO 10)
B3	1	NO. OF CORRECTION SPEEDS	(1 TO 5)
B4	1	NO. OF TR. WT. LOCS. PER PLANE	(1 OR 2)
B5	1	NO. OF CORR. WT. SETS REQ.	ANY NUMBER
B6	GRAMS	UNITS	("GRAMS" OR "OUNCES")

SECTION B – SENSOR DATA (IF NO AMPL. CAL. FACTOR AND PROBE ANGLE ARE GIVEN, 1 AND 0 ARE ASSUMED)

LINE NO.	SENSOR NO.	SENSOR TYPE*	AMPL. CAL. FACTOR	PROBE ANGLE (DEGR.)
B7.01	1	2	1.0	72°
B7.02				
B7.03				
B7.04				
B7.05				
B7.06				
B7.07				
B7.08				
B7.09				
B7.10				

(USE ADDITIONAL LINES IF REQUIRED)

*SENSOR TYPE – 1 = PROXIMITY PROBE
2 = VELOCITY PICKUP
3 = ACCELEROMETER

TABLE I cont.

SECTION B – BALANCE CORRECTION PLANE DATA

LINE NO.	PLANE NO.	NO. CORR. LOCATIONS	1ST LOC PAST ROTOR ZERO	MAX CORR. WEIGHT
B8.01	1	12	20	25
B8.02				
B8.03				
B8.04				
B8.05				

(USE ADDITIONAL LINES IF REQUIRED)

SECTION C – ROTOR OUT OF ROUNDNESS DATA (PROBES ONLY)

LINE NO.	SPEED (RPM)	AMPLITUDE (ANY UNIT)	PHASE (DEGR.)
C1.01			
C1.02			
C1.03			
C1.04			
C1.05			
C1.06			
C1.07			
C1.08			
C1.09			
C1.10			

(USE ADDITIONAL LINES IF REQUIRED)

SECTION D – UNCORRECTED ROTOR DATA (ONE LINE FOR EACH SENSOR)

LINE NO.	SPEED (RPM)	AMPLITUDE (ANY UNIT)	PHASE (DEGR.)
D1.01	8583	1.1	29
D1.02			
D1.03			
D1.04			
D1.05			
D1.06			
D1.07			
D1.08			
D1.09			
D1.10			

(USE ADDITIONAL LINES IF REQUIRED)

REPEAT SECTION D FOR EACH SPEED

TABLE I cont.

SECTION E – TRIAL WEIGHT ROTOR DATA
REPEAT THIS PAGE FOR EACH CORRECTION PLANE
LINE NUMBERS WILL VARY WITH EACH PLANE
EII.JJ.KK WILL BE LINE NUMBER FOR II TH PLANE, JJ TH SPEED, KK TH SENSOR.
THUS E03.01.07 IS LINE NUMBER FOR 3 RD PLANE, 1 ST SPEED, 7 TH SENSOR.
ORDER OF ENTRY IS IMPORTANT. (ONE LINE FOR EACH SENSOR)

LINE NO.	TRIAL WGT. SIZE	ANGULAR LOC. PAST ROTOR ZERO
E00.II	26.27	290°

LINE NO.	SPEED (RPM)	AMPLITUDE (ANY UNITS)	PHASE (DEGR.)
EII.JJ.01	8583	0.1	296
EII.JJ.02			
EII.JJ.03			
EII.JJ.04			
EII.JJ.05			
EII.JJ.06			
EII.JJ.07			
EII.JJ.08			
EII.JJ.09			
EII.JJ.10			

(USE ADDITIONAL LINES IF REQUIRED)

DATA FOR SAME TRIAL WEIGHT DIRECTLY OPPOSITE FIRST
OMIT IF B4=1 (ONE LINE FOR EACH SENSOR)

LINE NO.	SPEED (RPM)	AMPLITUDE (ANY UNITS)	PHASE (DEGR.)
EII.JJ.21			
EII.JJ.22			
EII.JJ.23			
EII.JJ.24			
EII.JJ.25			
EII.JJ.26			
EII.JJ.27			
EII.JJ.28			
EII.JJ.29			
EII.JJ.30			

(USE ADDITIONAL LINES IF REQUIRED)

REPEAT ALL PAGES OF SECTION E FOR EACH CORRECTION PLANE

BEST AVAILABLE COPY

TABLE II

```
CAD10        03:54EDT      09/03/76

     THIS IS RØTØR BALANCING PRØGRAM CADENSE* 10
     MECHANICAL TECHNØLØGY INC. ØWNS AND IS
     RESPØNSIBLE FØR THIS PRØGRAM

         * CADENSE IS A REGISTERED TRADE MARK OF M.T.I.

*************************************************************

A1   NEW

B1   1

B2   1

B3   1

B4   1

B5   1

B6   GRAMS

B7.01   1 2 1. 72

B8.01   1 12 20 25

D1.01   8583 1.1 29

E00.01   26.27 290

E01.01.01   8583 .1 296

DØ YØU WANT TØ SEE A LISTING ØF THIS INPUT (YES ØR NØ) NØ

DØ YØU WANT A DETAILED INPUT SUMMARY FØR RECORD
PURPØSES (YES ØR NØ) NØ
*************************************************************

RØTØR SENSITIVITY MATRIX


X-CØMPØNENT
SPEED NØ.    1 (    8583.0 RPM )
SENSØR                              ** PLANE NØ. **
  NØ.                1
```

TABLE II cont.

```
.......................................................................
     1  4.2149E-02


Y-COMPONENT
SPEED NO.   1 (   8583.0 RPM )
SENSOR                      ** PLANE NO. **
  NO.               1
.......................................................................
     1  -2.8269E-03


***********************************************************************



                 ** WEIGHT TO BE ADDED (IN GRAMS ) **
                 TOTAL CORRECTION WEIGHTS
 PLANE     WEIGHT          ANGLE          X-COMP          Y-COMP

   1        26.03953       -75.16292       6.66798       -25.17131


                 ** DISTRIBUTED CORRECTION WEIGHTS (IN GRAMS ) **
 PLANE  WEIGHT       HOLE      WEIGHT      HOLE
   1       0.00025     7          4.63580     9
          21.37587    10

EXPECTED RESIDUAL VIBRATION


UNCALIBRATED DATA

 SPEED   SENSOR    AMPLITUDE     PHASE
   NO.     NO.     ANY UNITS     (DEGR.)

   1        1        0.00000     -230.91746


ADJUSTED DATA (INCLUDES EFFECTS OF CALIBRATION FACTORS)
                   MEASURED VIBRATION               NET VIBRATION

 SPEED   SENSOR    AMPLITUDE     PHASE           AMPLITUDE      PHASE
   NO.     NO.     ANY UNITS     (DEGR.)         ANY UNITS      (DEGR.)

   1        1        0.00000     -158.91746        0.00000      -158.91746

WITH OUT-OF-ROUNDNESS --- SUM OF SQUARED RESID. =  0.337671E-17
                          RMS RESID.            =  0.183753E-08

NET VIBRATION         --- SUM OF SQUARED RESID. =  0.337671E-17
                          RMS RESID.            =  0.183753E-08
                          MAX. RESID./RMS       =  0.100000E+01
```


BEST AVAILABLE COPY

TABLE II cont.

BEST AVAILABLE COPY

```
**********************************************************************

A1  REPT

D1.01  8583 .1 296

E00.01  26.27 110.

E01.01.01  8583 1.1 29

DØ YØU WANT TØ SEE A LISTING ØF THIS INPUT (YES ØR NØ) NØ

DØ YØU WANT A DETAILED INPUT SUMMARY FØR RECØRD
PURPØSES (YES ØR NØ) NØ

**********************************************************************

RØTØR SENSITIVITY MATRIX


X-CØMPØNENT
SPEED NØ.   1 (    8583.0 RPM )
SENSØR                         ** PLANE NØ. **
   NØ.          1
......................................................................
     1   4.2149E-02

Y-CØMPØNENT
SPEED NØ.   1 (    8583.0 RPM )
SENSØR                         ** PLANE NØ. **
   NØ.          1
......................................................................
     1  -2.8269E-03
```

TABLE II cont.

BEST AVAILABLE COPY

```
***********************************************************************

              ** WEIGHT TØ BE ADDED (IN GRAMS ) **
              TØTAL CØRRECTIØN WEIGHTS
 PLANE     WEIGHT      ANGLE         X-CØMP          Y-CØMP

   1        2.36723    -168.16291     -2.31689        -0.48559

              ** DISTRIBUTED CØRRECTIØN WEIGHTS (IN GRAMS ) **
 PLANE  WEIGHT      HØLE    WEIGHT      HØLE
   1     0.67225      6      1.76106      7


EXPECTED RESIDUAL VIBRATIØN


UNCALIBRATED DATA

 SPEED   SENSØR    AMPLITUDE      PHASE
  NØ.     NØ.      ANY UNITS      (DEGR.)

   1       1        0.00000       -59.13322


ADJUSTED DATA (INCLUDES EFFECTS ØF CALIBRATIØN FACTØRS)
                   MEASURED VIBRATIØN              NET VIBRATIØN

 SPEED   SENSØR    AMPLITUDE      PHASE           AMPLITUDE        PHASE
  NØ.     NØ.      ANY UNITS      (DEGR.)         ANY UNITS        (DEGR.)

   1       1        0.00000       12.86673         0.00000         12.86678

WITH ØUT-ØF-RØUNDNESS --- SUM ØF SQUARED RESID. =   0.553731E-18
                          RMS RESID.            =   0.744131E-09

NET VIBRATIØN         --- SUM ØF SQUARED RESID. =   0.553731E-18
                          RMS RESID.            =   0.744131E-09
                          MAX. RESID./RMS       =   0.100000E+01

***********************************************************************
```

SECTION V

F100 ADVANCED TECHNOLOGY ENGINE TRIM BALANCING DEMONSTRATION

A. Introduction

As part of the AFAPL program, on August 25th and 26th, 1977, a balancing demonstration was performed on an F100 engine at the NASA Lewis High Altitude Test Facility in Cleveland, Ohio. This report describes both the procedure used in the demonstration and the successful results. The effectiveness of the computerized trim balancing procedure and its straightforward application to this advanced engine were demonstrated.

B. NASA-Lewis Test Facility

The demonstration was conducted at the NASA-Lewis High Altitude Test Facility, which allows jet engine operation under controlled inlet air temperature and simulated altitudes to 30,000 + feet. Because the electrical power requirements of the test chamber support equipment (air compressors, etc...) are quite substantial and costly, operational testing of the F100 engine is restricted to the hours of midnight to 7:00 A.M. The test chamber control room and the chamber environmental support equipment is located in adjacent buildings. Because of the sophisticated testing facility and nature of test operations, only two test runs per night could be completed.

C. Trim Balancing Procedure and Equipment Setup

Trim balancing of the F100 required that a total of three test runs be made to allow the following data sets to be recorded:

1. Baseline Vibration Response
2. Trial Weight Installed Vibration Response
3. Correction Weight Installed Vibration Response

The most effective approach to high-speed balancing is obtained when the critical speeds and the vibratory mode shapes of the rotor system are defined for each of the resonances traversed during operation. This information then would assist in selecting for each resonance the balancing planes which would be at optimum locations, for the engine design and the rotor response. This, of course, is an optimum approach, and such data is not always available. In such cases where analytical information on rotor mode shapes and critical speeds is not available for pre-balancing decision-making, assumptions are made based on information gained from baseline data sets gathered during initial testing, and from past experiences of rotor systems of similar type and construction. The final consideration is, naturally, the available access to locations on the rotor to place the trial and correction weight sets.

The vibration data which yields information on the engine sensitivity (in this case, vibration responses from two velocity transducers mounted vertically and horizontally on the inlet housing for imbalance of the first fan stage), was in the form of synchronous vibration amplitude and the angular direction of the vibration relative to a specific position on the rotor. Gathering this data is accomplished in a rather straightforward manner by using the following equipment:

1. A speed-sending tachometer that triggers at a specific rotor location In this particular test, a magnetic tach pickup located at the No. 1 Bearing triggered and produced a voltage output when a tang on the rotor passed the tach pickup surface, thus giving both a speed (R.P.M.) signal and a rotor-position-locating reference (the start of the output voltage signal rise). This signal was then input to a square-wave

generator, which accepts an impulse input signal and outputs a constant amplitude square-wave signal that is frequency and phase coherent to the input (a clean and well defined signal of constant voltage level is usually more desirable for use with tracking filters and phasemeters.)

2. A dual-channel tracking filter, that is "tuned" by the square-wave generator output signal, through which the vibration sensing transducer signal may be filtered. The filtered data amplitude (which now represents only the synchronous amplitude response) is displayed by front panel meters indicating voltage level. Knowing the transducer calibration sensitivity (in terms of output volts per unit amplitude), accurate measurements of the synchronous amplitudes may be made. Additionally, the tracking filter provides output signals compatible with an X-Y recorder, thus allowing on-line plotting of synchronous response amplitude versus R.P.M.

3. A phasemeter which detects the phase angle between two applied signals and digitally indicates the values on front panel meters. In this test setup, the two applied signals are the tach signal, which is paralleled from the tracking filter, and the filtered synchronous amplitude signal from the tracking filter. This then allows angular phase measurement of the response amplitude relative to a specific rotor location.

D. Trim Balance Demonstration

Plots of the engine vibration in the "as-is" condition were made, and showed that the maximum synchronous response occurred in the 5800 to 6000 R.P.M. range of operation (see Figure 9). Without a prior vibration anaylsis to identify exactly where the critical speeds of the engine were, the 5800 to 6000 R.P.M. range was assumed to be the first critical speed of the engine. Data was recorded at several speeds (see Table III) for input to the balancing program.

The next phase of testing required the placement of a trial weight in the engine. A trial weight of 12.128 grams was placed on the trim balancing weight ring of the first fan stage.

A second test run was then made, again plotting the synchronous displacement of the two vibration probes. As may be seen in Figure 10, a change in response occurred because of the large additional implanted balance. The speed points used in the first run were repeated, and the response data logged for input to the balancing program.

After reviewing the "as-is" engine vibration response of Figure 9, a three-speed, single-correction-plane balancing run was made. Two points near the resonance (98 Hz and 100 Hz), and one additional data point higher in the speed range (149 Hz) were used. The input data to the CAD 10 computer program (described in the Introduction) is listed in Table IV, with the instrumentation setup as shown in Figure 11. The setup data, initial vibration response, and the effects of the trial weight are all input data items. The GE Timesharing system, available worldwide, was accessed by a portable computer terminal with an acoustic coupler via a telephone line. The resulting correction weight set called for 20.89 grams at 172° (measured from the speed tang in the direction of rotation).

There were only two classes of correction weights available: 12.1 grams and 5.0 grams. To further complicate the problem of adding the proper correction weight, there were 36 holes in the balancing plane but fifteen (15) were previously filled with a weight or a rivet. Table V shows the distribution of the available holes to apply the correction weight. CAD 12, the weight distribution program (described in the Introduction), was used to select the optimum location of the weights available to result in the correction weight vector required. The weights selected and location are listed below:

Hole Location	Weight Size
17	5.0
21	5.0
20	12.1
	22.1

This selection was predicted to reduce the residual unbalance from 20.88 grams at 172° to 0.68 at 206°. These weights were applied and the resultant reduction in vibration can be seen in Figure 12. This check run is the proof run with the calculated effective correction weight of 20.88 grams installed in the engine. It was performed in the same manner as the two previous runs. The synchronous displacement response of each of the two transducers was plotted as before, and data was recorded at the same speed points to assess further the unbalance response of the engine (see Table IV for data).

Assessment of the plotted curves of Figure 13 shows the excellent improvement achieved in the unbalance response by installation of the correction weights. However, although the plotted curves are essentially "flat" in response, the level of response is nearly a constant amplitude close to one mil peak-to-peak. While a response of this level is within acceptable limits, it indicates that a fairly high overall amount of synchronous forced vibration still exists within the engine's operational speed range. This forced vibration is due to remaining imbalance residuals which are distributed along the entire rotor, and which could not be affected by the fan balancing process described above.

TABLE III

BALANCING DATA POINT VALUES

AS-IS RUN

	PROBE			
	VIFIX		VIFIY	
SPEED (R.P.M.)	AMP MILS P/P	PHASE	AMP MILS P/P	PHASE
5880	3.05	230°	2.65	324°
6000	2.65	251°	2.65	346°
8940	1.45	21°	1.30	117°

TRIAL WEIGHT RUN (12.128 grams)

	PROBE			
	VIFIX		VIFIY	
SPEED	AMP MILS P/P	PHASE	AMP MILS P/P	PHASE
5880	4.23	233°	3.80	331°
6000	4.22	265°	4.03	355°
8940	2.03	7°	1.68	98°

BALANCED ENGINE RUN

	PROBE			
	VIFIX		VIFIY	
SPEED	AMP MILS P/P	PHASE	AMP MILS P/P	PHASE
5880	1.10	107°	.96	161°
8940	1.30	130°	1.45	213°

TABLE IV

MULTIPLANE – MULTISPEED BALANCING
INPUT DATA SHEET

SECTION A – COMMANDS FOR CONTROL OF CALCULATION

LINE NO.	DATA	INPUT REQUEST	OPTION	MEANS
A1	NEW	COMMAND	"NEW"	GIVE COMPLETE INPUT

NOTE: A1 WILL ALSO BE REQUESTED AFTER CALCULATIONS ARE COMPLETED.
THE COMMAND: "REPT" MEANS SECTION B IS BYPASSED IN A NEW CALCULATION
"STOP" MEANS THE USE OF THE PROGRAM IS COMPLETE.

SECTION B – SETUP DATA (USE ONLY IF "NEW" COMMAND IS GIVEN ON LINE A1)

LINE NO.	DATA	INPUT REQUEST	RANGE
B1	2	NO. OF SENSORS	(1 TO 20)
B2	1	NO. OF CORRECTION PLANES	(1 TO 10)
B3	3	NO. OF CORRECTION SPEEDS	(1 TO 5)
B4	1	NO. OF TR. WT. LOCS. PER PLANE	(1 OR 2)
B5	2	NO. OF CORR. WT. SETS REQ.	ANY NUMBER
B6	GRAMS	UNITS	("GRAMS" OR "OUNCES")

SECTION B – SENSOR DATA (IF NO AMPL. CAL. FACTOR AND PROBE ANGLE ARE GIVEN, 1 AND 0 ARE ASSUMED)

LINE NO.	SENSOR NO.	SENSOR TYPE*	AMPL. CAL. FACTOR	PROBE ANGLE (DEGR.)
B7.01	1	3	1	90
B7.02	1	3	1	180
B7.03				
B7.04				
B7.05				
B7.06				
B7.07				
B7.08				
B7.09				
B7.10				

(USE ADDITIONAL LINES IF REQUIRED)

***SENSOR TYPE – 1 = PROXIMITY PROBE**
2 = VELOCITY PICKUP
3 = ACCELEROMETER

MTI-16411

TABLE IV - cont.

SECTION E – TRIAL WEIGHT ROTOR DATA

REPEAT THIS PAGE FOR EACH CORRECTION PLANE

LINE NUMBERS WILL VARY WITH EACH PLANE

EII.JJ.KK WILL BE LINE NUMBER FOR II TH PLANE, JJ TH SPEED, KK TH SENSOR.

THUS E03.01.07 IS LINE NUMBER FOR 3 RD PLANE, 1 ST SPEED, 7 TH SENSOR.

ORDER OF ENTRY IS IMPORTANT. (ONE LINE FOR EACH SENSOR)

LINE NO.	TRIAL WGT. SIZE	ANGULAR LOC. PAST ROTOR ZERO
E00.II	12.13	0

LINE NO.	SPEED (RPM)	AMPLITUDE (ANY UNITS)	PHASE (DEGR.)
EII.JJ.01	149	203	7
EII.JJ.02	149	168	98
EII.JJ.03	100	422	265
EII.JJ.04	100	403	355
EII.JJ.05	98	423	233
EII.JJ.06	98	380	331
EII.JJ.07			
EII.JJ.08			
EII.JJ.09			
EII.JJ.10			

(USE ADDITIONAL LINES IF REQUIRED)

DATA FOR SAME TRIAL WEIGHT DIRECTLY OPPOSITE FIRST

OMIT IF B4=1 (ONE LINE FOR EACH SENSOR)

LINE NO.	SPEED (RPM)	AMPLITUDE (ANY UNITS)	PHASE (DEGR.)
EII.JJ.21			
EII.JJ.22			
EII.JJ.23			
EII.JJ.24			
EII.JJ.25			
EII.JJ.26			
EII.JJ.27			
EII.JJ.28			
EII.JJ.29			
EII.JJ.30			

(USE ADDITIONAL LINES IF REQUIRED)

REPEAT ALL PAGES OF SECTION E FOR EACH CORRECTION PLANE

TABLE IV - cont.

SECTION B – BALANCE CORRECTION PLANE DATA

LINE NO.	PLANE NO.	NO. CORR. LOCATIONS	1ST LOC PAST ROTOR ZERO	MAX CORR. WEIGHT
B8.01	1	36	0	12
B8.02				
B8.03				
B8.04				
B8.05				

(USE ADDITIONAL LINES IF REQUIRED)

SECTION C – ROTOR OUT OF ROUNDNESS DATA (PROBES ONLY)

LINE NO.	SPEED (RPM)	AMPLITUDE (ANY UNIT)	PHASE (DEGR.)
C1.01			
C1.02			
C1.03			
C1.04			
C1.05			
C1.06			
C1.07			
C1.08			
C1.09			
C1.10			

(USE ADDITIONAL LINES IF REQUIRED)

SECTION D – UNCORRECTED ROTOR DATA (ONE LINE FOR EACH SENSOR)

LINE NO.	SPEED (RPM)	AMPLITUDE (ANY UNIT)	PHASE (DEGR.)
D1.01	149	145	21
D1.02	149	130	117
D1.03	100	265	251
D1.04	100	265	346
D1.05	98	305	230
D1.06	98	265	324
D1.07			
D1.08			
D1.09			
D1.10			

(USE ADDITIONAL LINES IF REQUIRED)

REPEAT SECTION D FOR EACH SPEED

TABLE V

Hole No.	Angular Location (°)	Hole Condition	Hole No.	Angular Location (°)	Hole Condition
36	355	O	18	175	O
35	345	O	17	165	O
34	335	R	16	155	R
33	325	O	15	145	O
32	315	O	14	135	W
31	305	R	13	125	R
30	295	O	12	115	W
29	285	W	11	105	O
28	275	R	10	95	R
27	265	O	9	85	O
26	255	O	8	75	O
25	245	R	7	65	R
24	235	O	6	55	O
23	225	O	5	45	O
22	215	R	4	35	R
21	205	O	3	25	O
20	195	O	2	15	O
19	185	R	1	5	R

For each Balance-Weight Station, denote with following key:

O - Hole
R - Rivet
W - Weight

SECTION VI

W-PAFB EXPERIMENTAL RUB RIG

A. Introduction

This particular test rig is installed at W-PAFB for compressor seal wear evaluations. The rotating element of the test rig consists of a rolling element-supported shaft with the compressor wheel overhung from one end, and a drive flange overhung from the other. The rotor is driven from a gear box through a flex-disk coupling (Bendix type).

B. Test Configuration and Instrumentation

From a critical speed and mode shape calculation which had been performed by MTI prior to the balancing described herein, it appeared that up to three critical speeds might be encountered below 12,000 R.P.M. (see Figures 14 through 16). The test rig was not designed for effective in-place balancing of the complete rotor. There were three balancing planes available on the rotor: two were located on the flanges of the coupling connecting the drive gear shaft to the test rig rotor, and one at the overhang disk. At the coupling location, two sensors were installed for rotor displacement measurements. As a speed signal and phase angle reference generator, a photo-optic probe was used. Attempts to use white tape as a light-reflective surface for triggering the photo-optic sensor were unsuccessful, and the tape had to be ultimately replaced by a black-and-white painted surface.

MTI portable balancing equipment, consisting of a dual-channel tracking filter and a phasemeter, was installed in the test cell in parallel with W-PAFB-owned equipment for data acquisition.

C. Balancing Procedure and Results

For balancing data acquisition, five test runs were made, one "as-is" condition and with weights placed at 0 degrees and 180 degrees in each of the two coupling planes, at a speed around 5000 rpm. The calculated and installed correction weights were 6.13 grams in plane 1 at an angle of 71 degrees, and 3.46 grams at 338 degrees. Plane 1 was the coupling flange adjacent to the gearbox. With the correction weights installed, the previously observed amplitude rise just below 5000 R.P.M. disappeared, and amplitudes now showed a similar rise between 8000 and 9000 R.P.M., peaking around 10,000 R.P.M. The results, as presented in Figures 17 and 18, are somewhat misleading, because rotor speed is shown logarithmically and, therefore, creates the impression that just one critical speed has been suppressed by balancing. The analysis indicated that possibly three closely spaced critical speeds may occur in that speed range. If the rotor actually had gone through the third critical speed below 12,000 R.P.M., fortuitous circumstances might have been a contributing factor, since more than the two balancing speeds and sensors provided should be required for systematic balancing of all three critical speeds in the speed range. In fact, it was concluded at that time that an accelerometer in the bearing housing next to the compressor wheel should be provided for a future balancing run aimed at reducing the amplitude peak.

SECTION VII

CONCLUSIONS

A. The Computerized Balancing Procedure provides accurate trim correction weights to reduce rotor vibration caused by unbalance. All the balancing demonstrations yielded correction weights which resulted in an acceptable engine vibration condition or indication of accurate predictions when the vibration levels were very low. These accurate corrections can actually be obtained by using course weights which are vectorally positioned to provide the proper solution. This effect was dramatically shown in the F100 engine demonstration.

B. The defined computerized procedure minimizes the possibility for operator error and increases the prediction accuracy while normally reducing the number of runs as compared to the present manual operation. The vibration data for input to the program is precisely defined in the program writeup and balancing procedure. This provides the operator with a compact instruction sheet and documentation of the results for engine rig operating history.

C. The Computerized Balancing Procedure has indications of potential use as a trim balancing tool for production and overhaul operations. As shown, particularly in the TF30 engine demonstration, the number of balancing steps can be reduced while increasing the quality of the final product. By storing the engine sensitivity data (influence coefficients) within the data processor, correction weights can usually be calculated from initial, first-run vibration signatures. This will result in a rapid trim balancing capability with a better final balance condition.

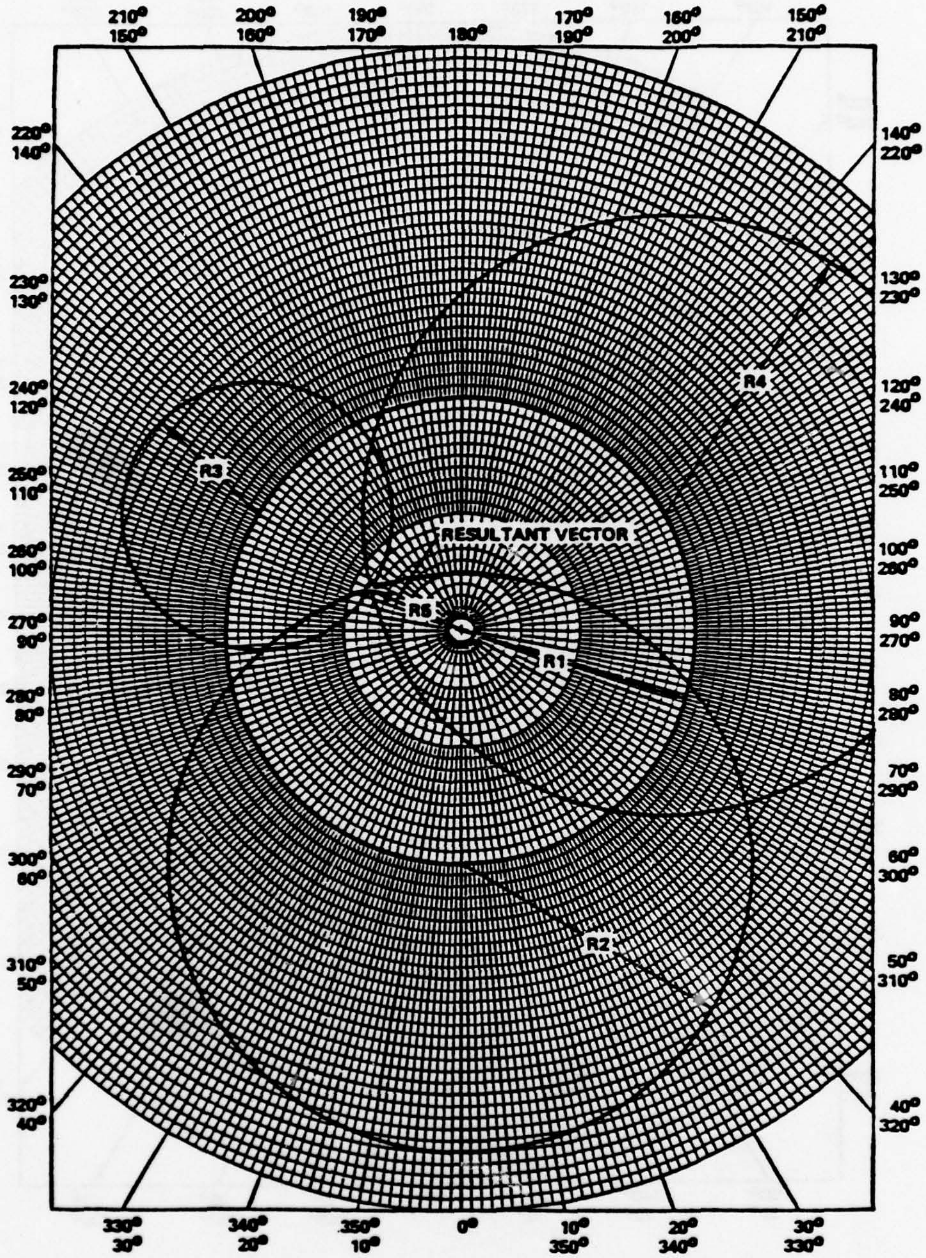
D. The Computerized Influence Coefficient Balancing System is a powerful piece of laboratory equipment which can provide precision balancing of unique, high-speed equipment. For sensitive rotor systems, experimental studies can be performed to determine the balancing planes, balancing speeds, and instrumentation required to balance a system through several critical speeds to acceptable vibration levels.

SECTION VIII

RECOMMENDATIONS

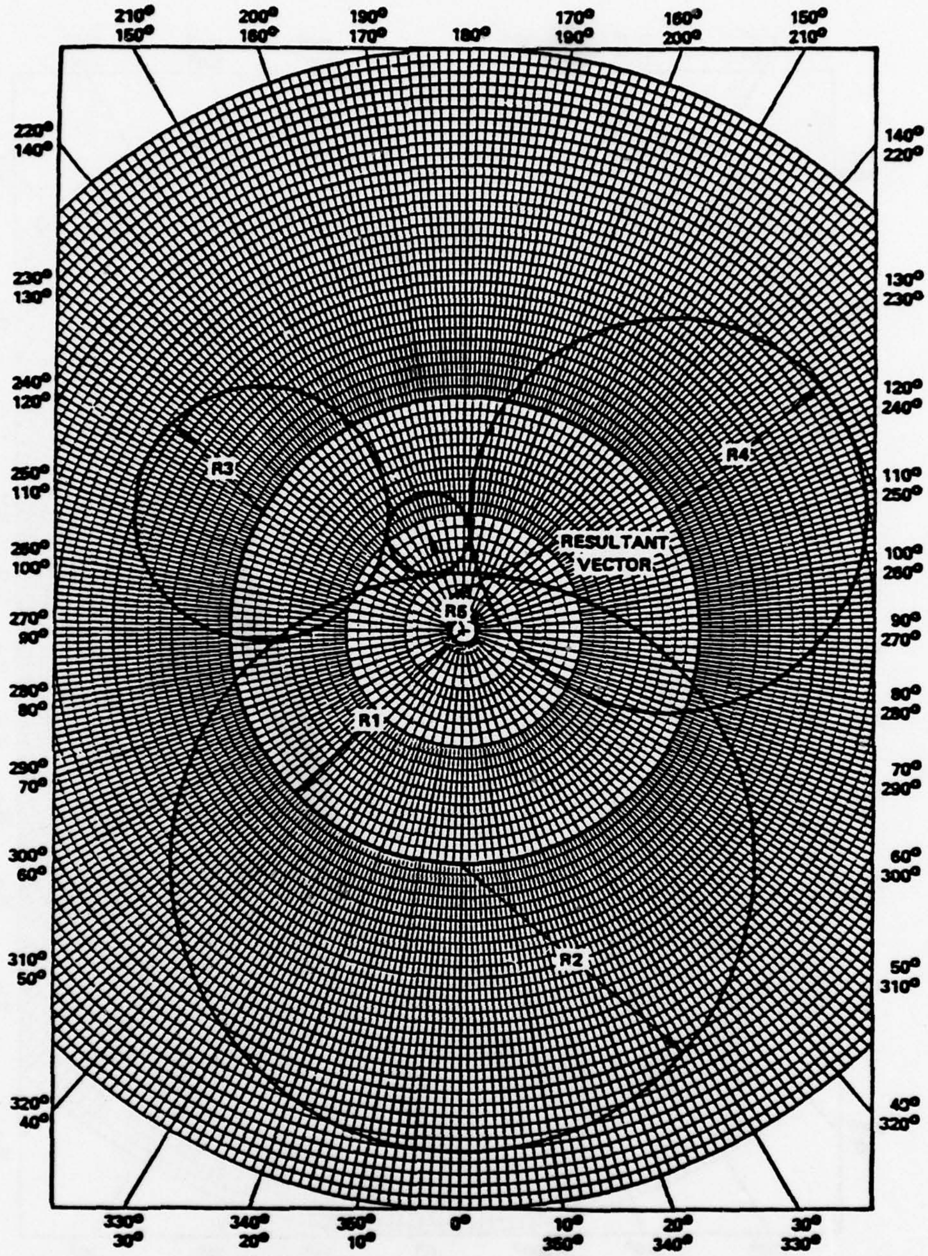
A. The Computerized Influence Coefficient Balancing Procedure has shown promise as a production Trim Balancing System. To do this rapidly, engine sensitivity data (influence coefficients) must be stored and retrieved as required. The balance weights calculated will only be as accurate as the base of data used to determine them. Engine model Influence Coefficient data should be experimentally determined to establish a norm and the deviation from this norm. These tests would determine the accuracy of stored vibration data relative to each engine tested.

B. A prototype Automated Trim Balancing System should be installed at an Air Logistic Center for one specific engine model. Based on the demonstrations described in this report, the Automated Trim Balancing System can provide a substantial cost savings and better manpower facilities utilization with this equipment. This type system should then be applied to all engines for trim balancing and expanded to include vibration diagnostic capabilities.



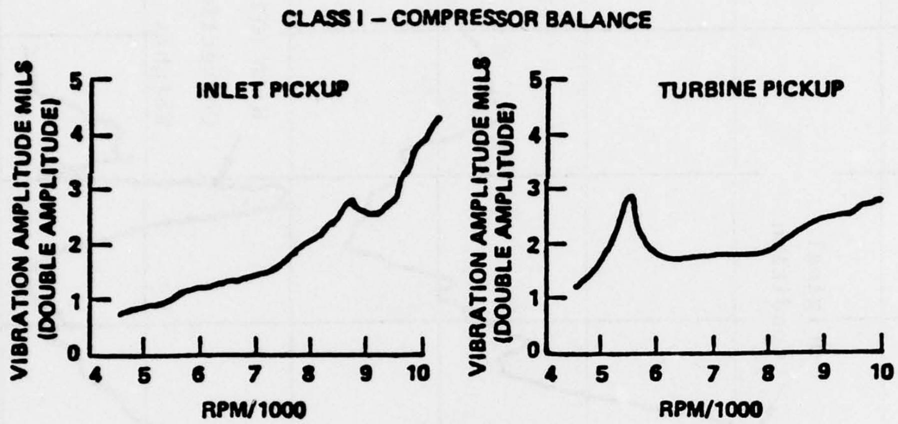
R1 - Vibration vector for initial run
R2 - Vibration with trial wt. at 0°
R3 - Vibration with trial wt. at 120°
R4 - Vibration with trial wt. at 240°
R5 - Vector for applying correction wt.

Fig. 1 Vibration Amplitude and Trial Weights

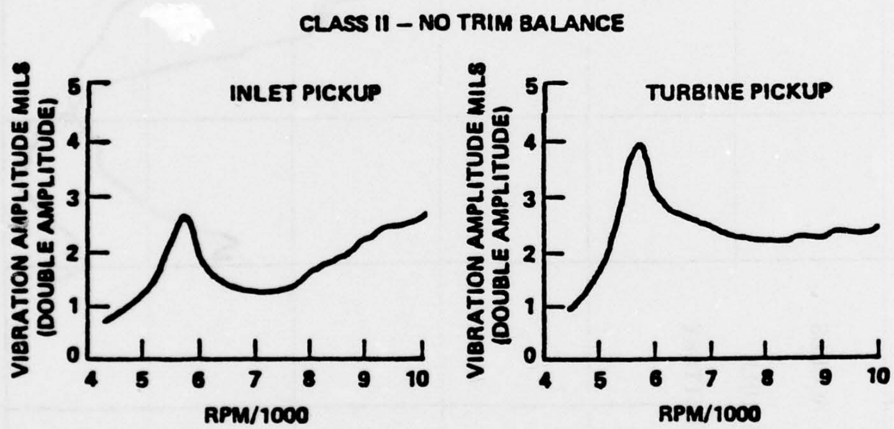


R1 - Vibration Vector for initial run
R2 - Vibration with trial wt. at 0°
R3 - Vibration with trial wt. at 120°
R4 - Vibration with trial wt. at 240°
R5 - Vector for applying correction wt.

Fig. 2 Vibration Amplitude and Trial Weights



Balanceable



Not Balanceable

Fig. 3 TF30 Engine Trim Balance Classifications

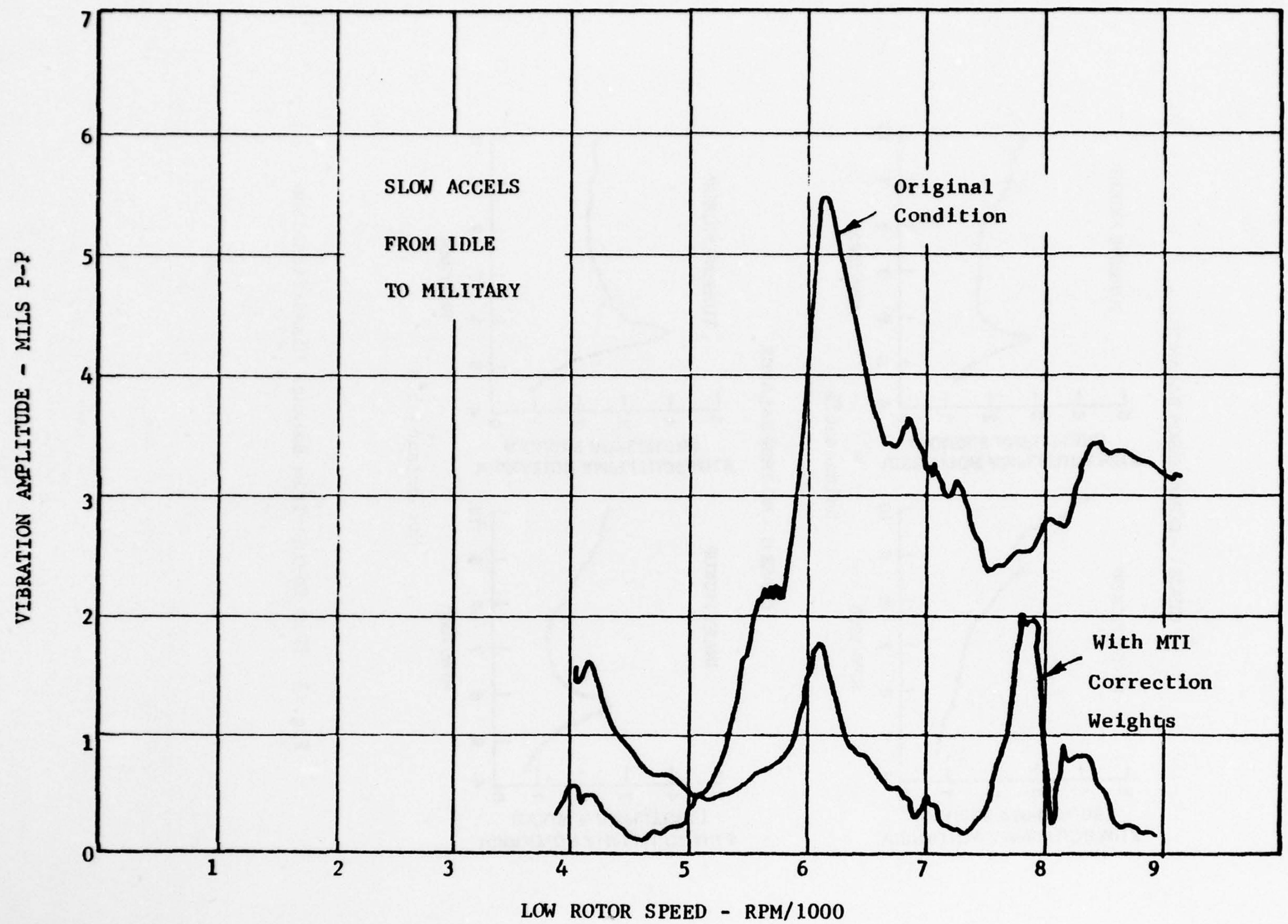


Fig. 4 TF30P-3 Trim Balancing Demonstration with the MTI Balancing System at Tinker Air Force Base

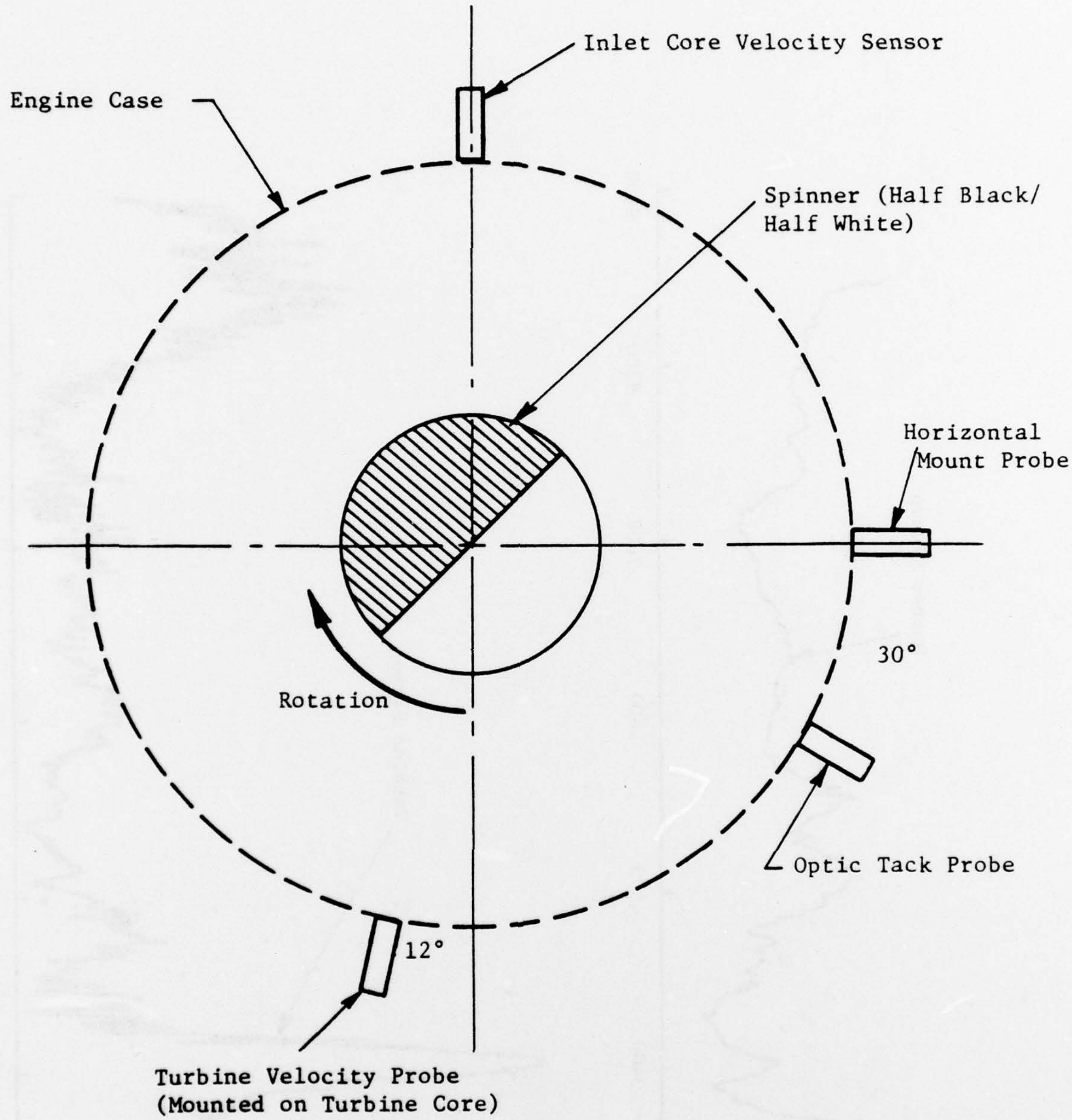


Fig. 5 TF41 Instrumentation Setup (Forward Looking AFT)

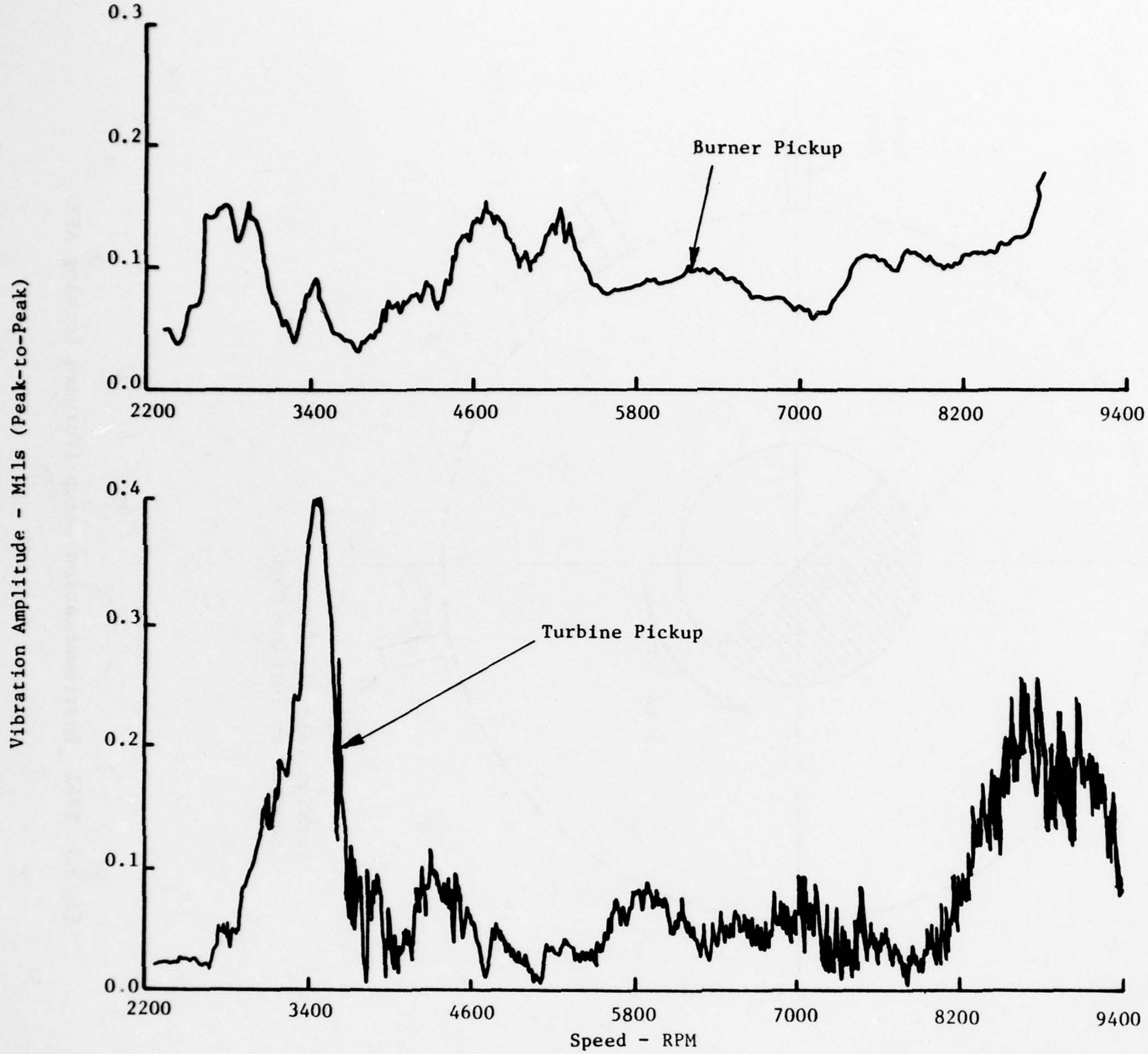


Fig. 6 TF41 Engine Response in the "As-Is" Condition

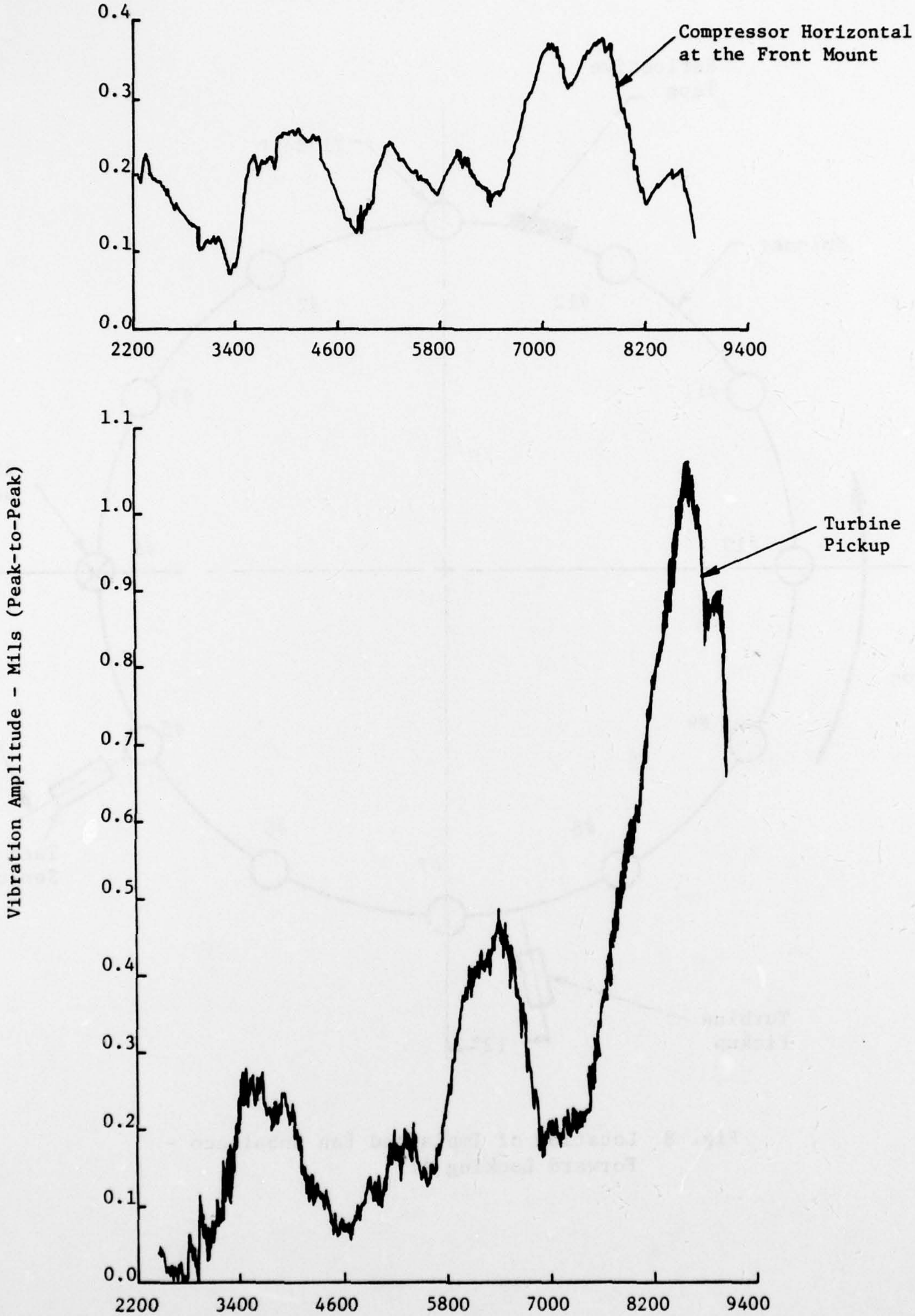


Fig. 7 TF41 Engine Response with a Weight Implanted in the Front Spinner

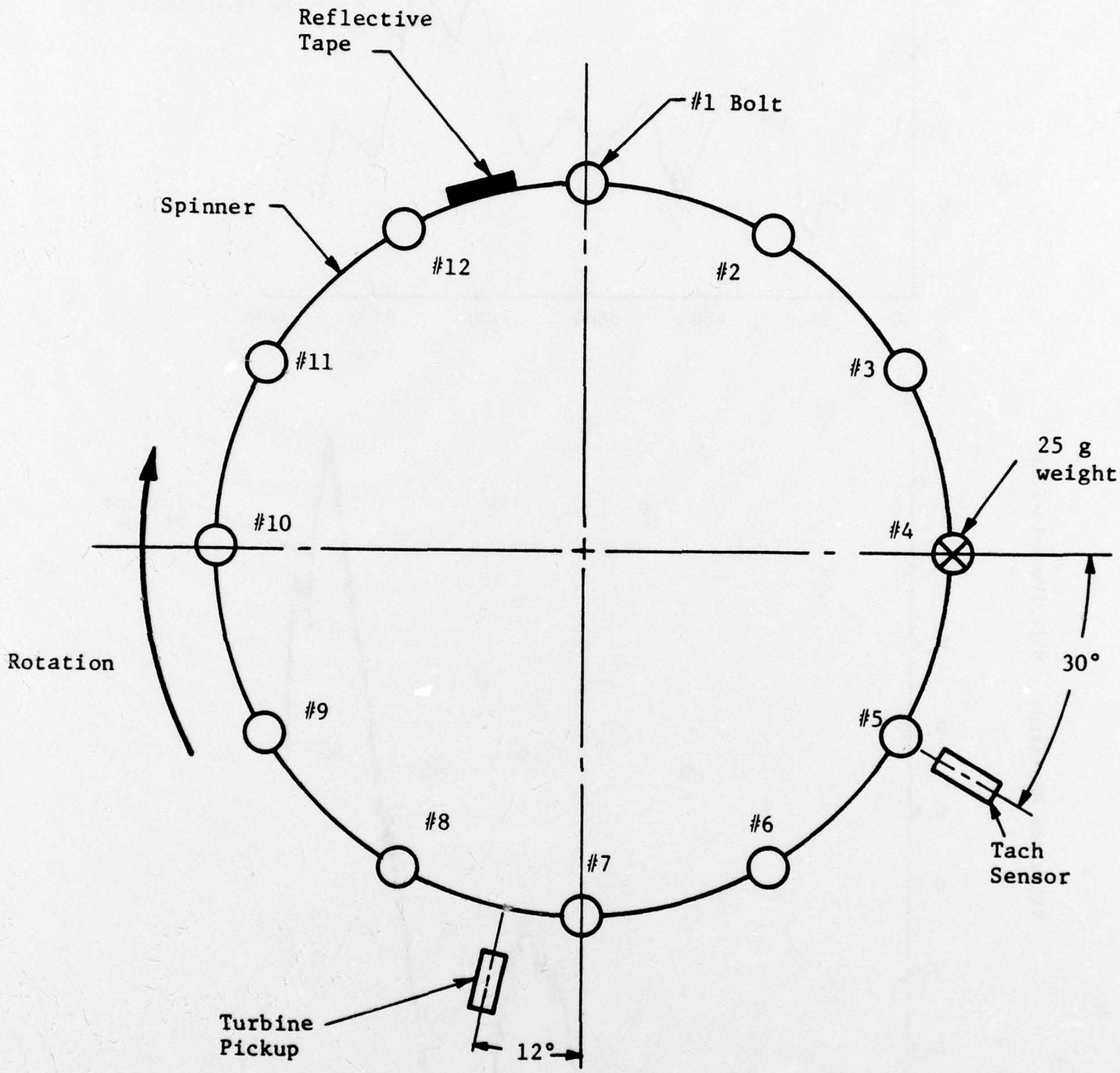


Fig. 8 Location of Implanted Fan Unbalance -
Forward Looking AFT

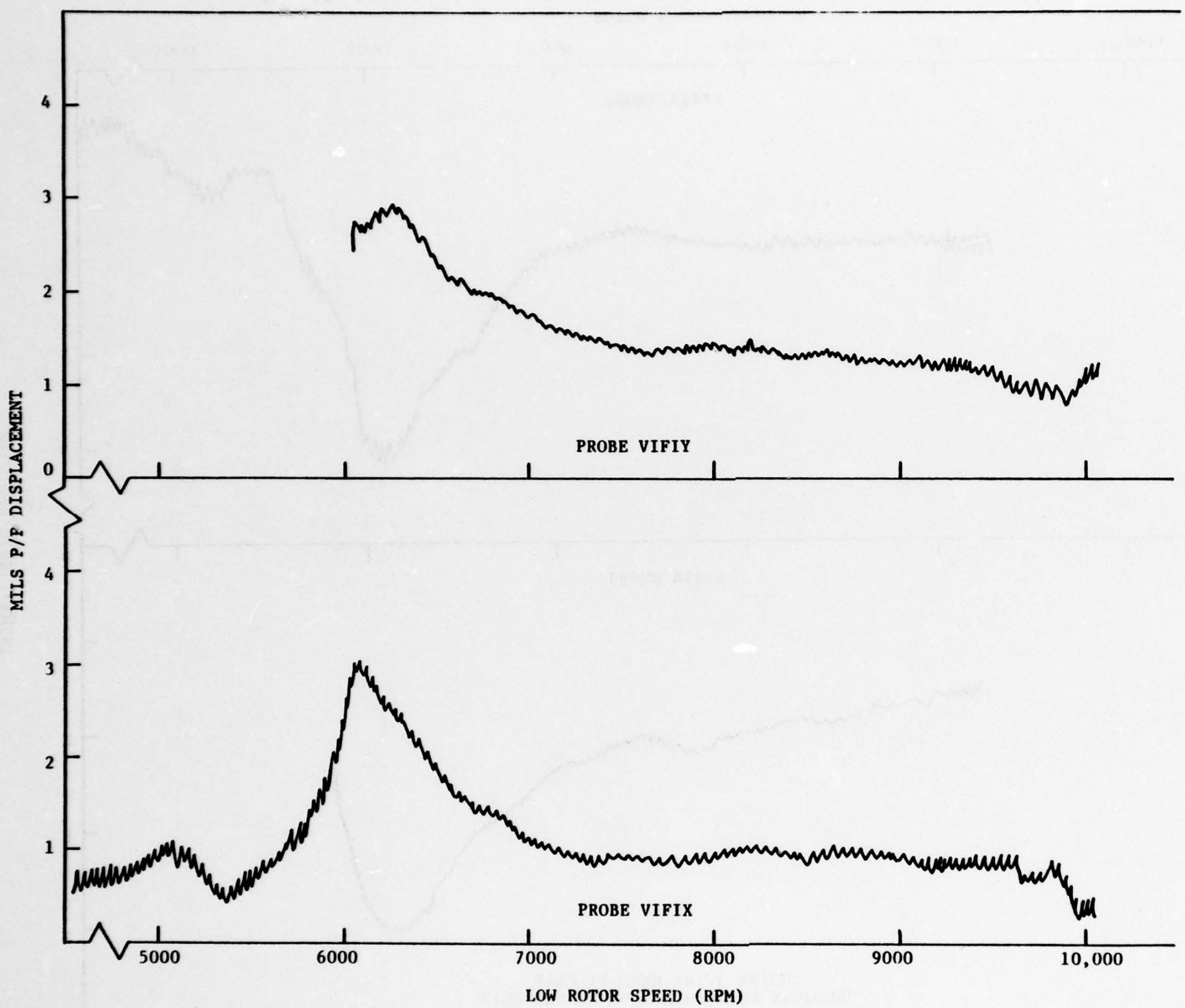


Fig. 9 F100 Synchronous Vibration Response - Baseline (AS-IS) Condition

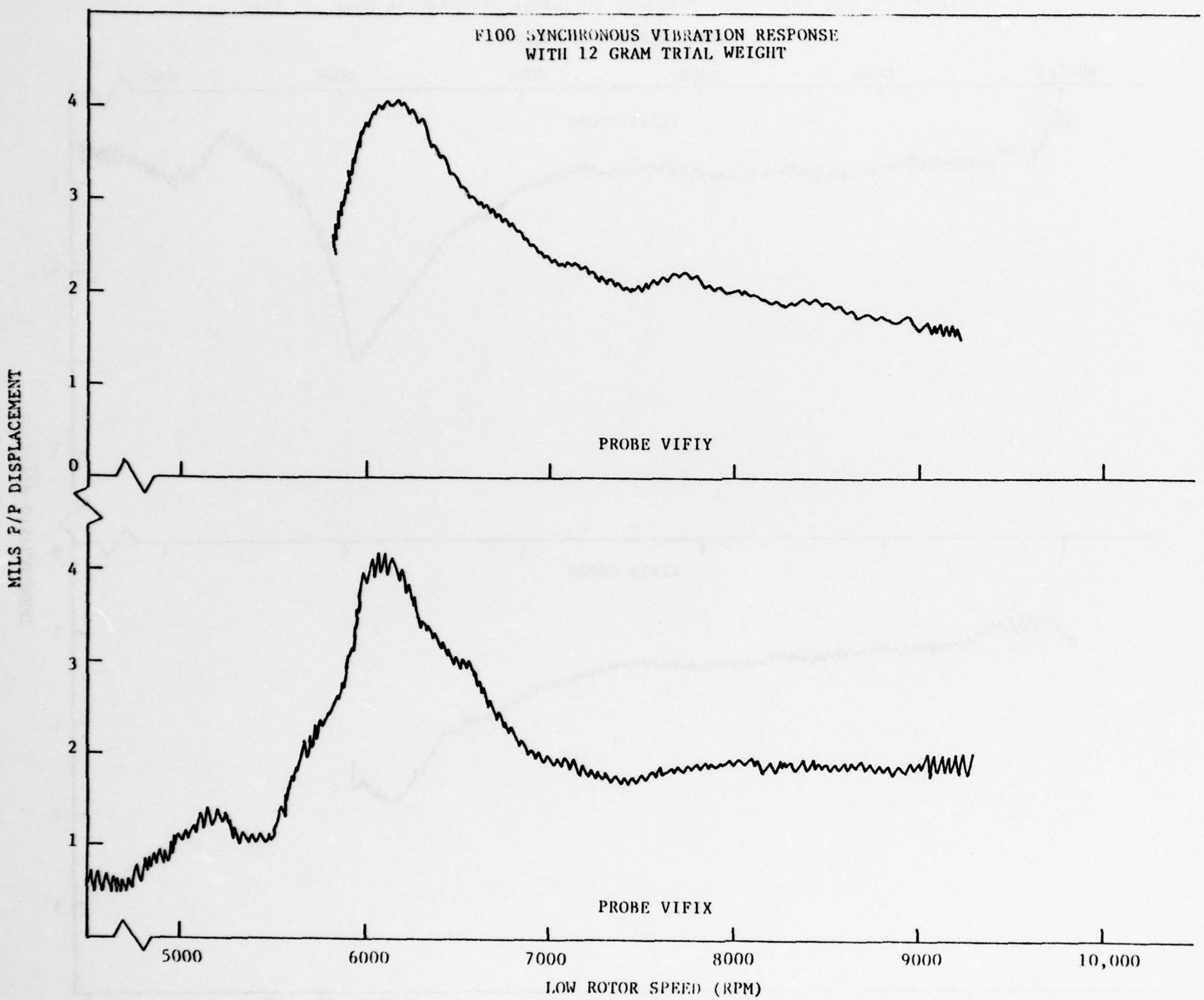


Fig. 10 F100 Synchronous Vibration Response with 12-Gram Trial Weight

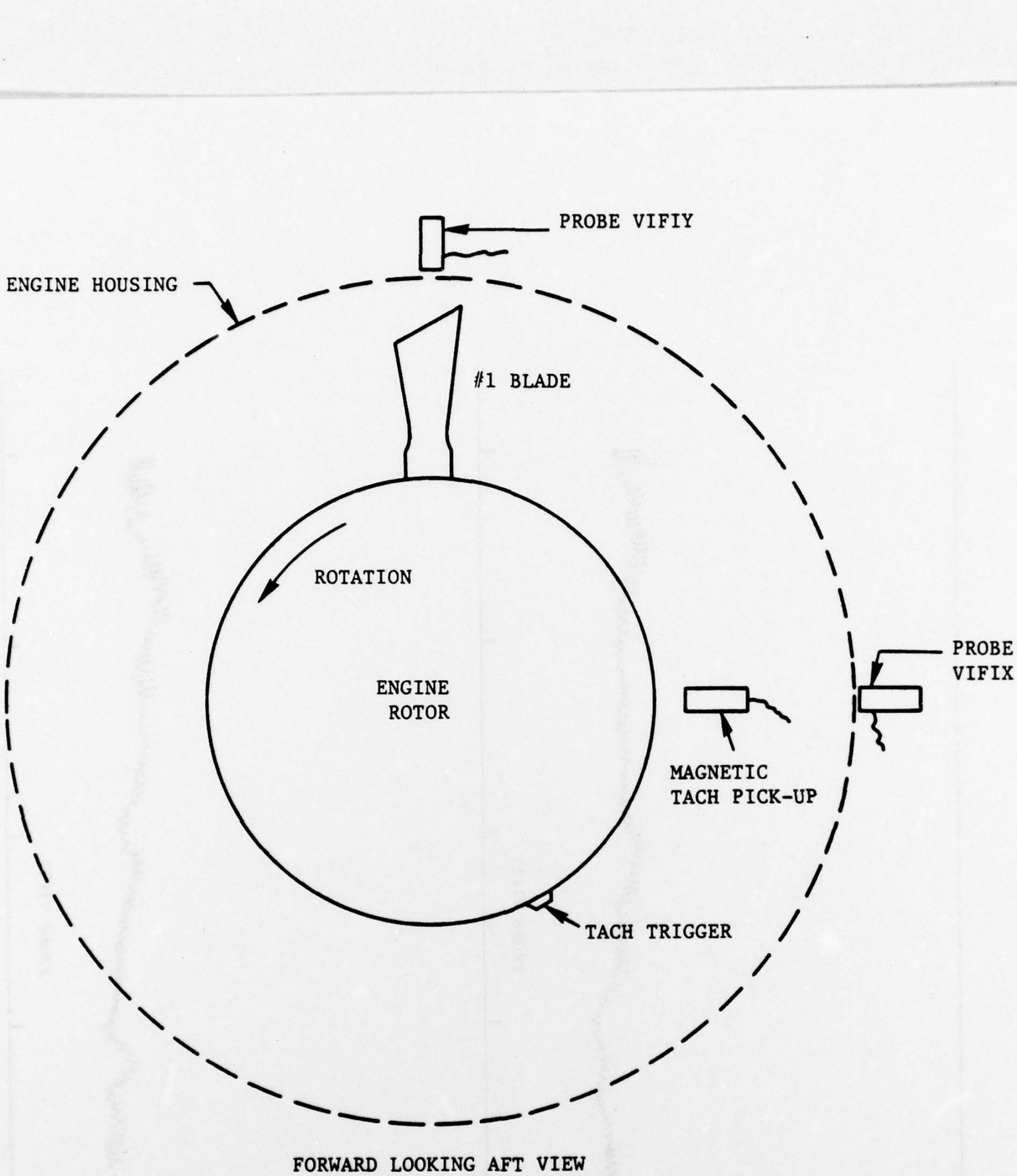


Fig. 11 Orientation of Transducers Used for Balancing the F100

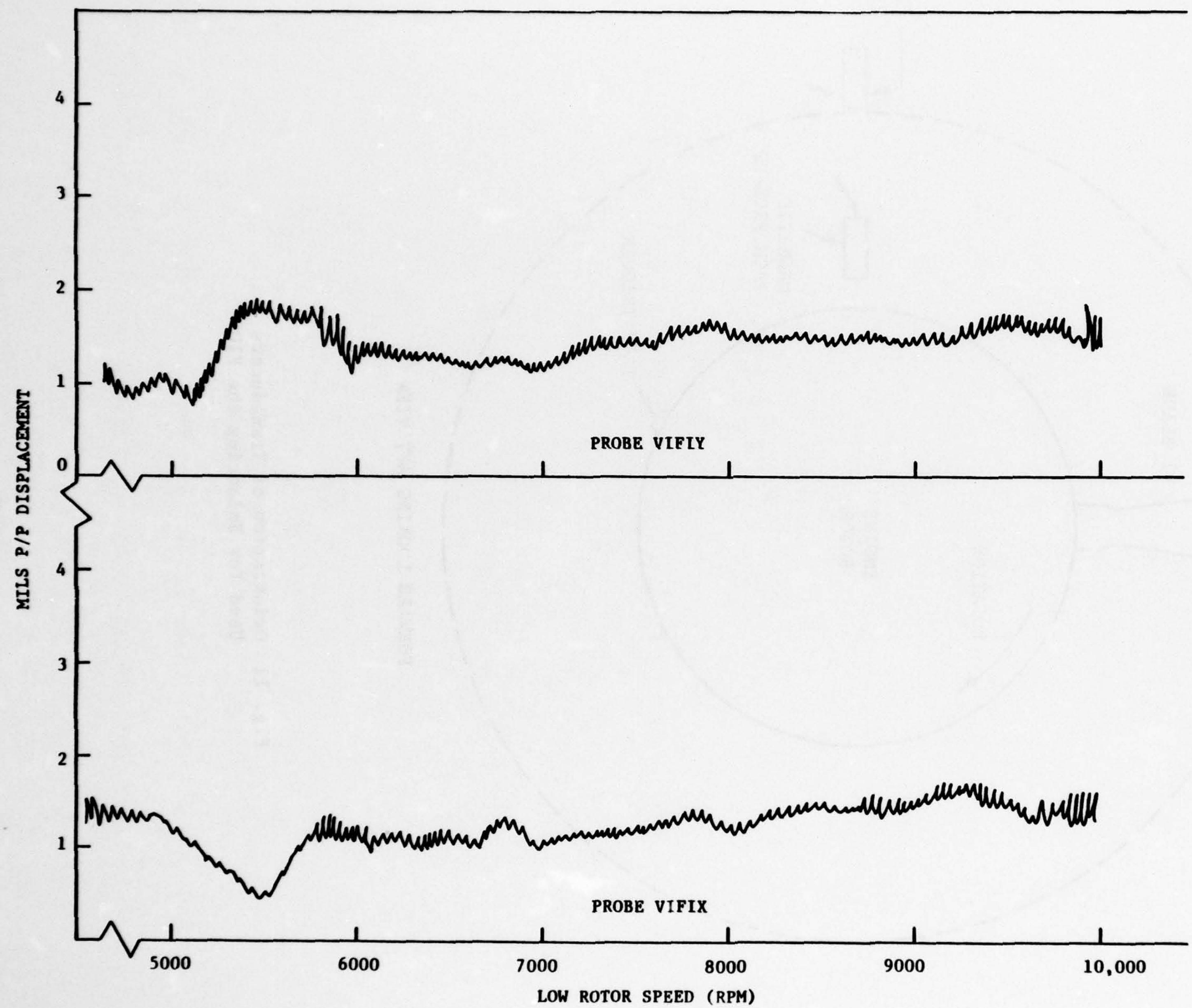


Fig. 12 F100 Synchronous Vibration Response with Correction Weights

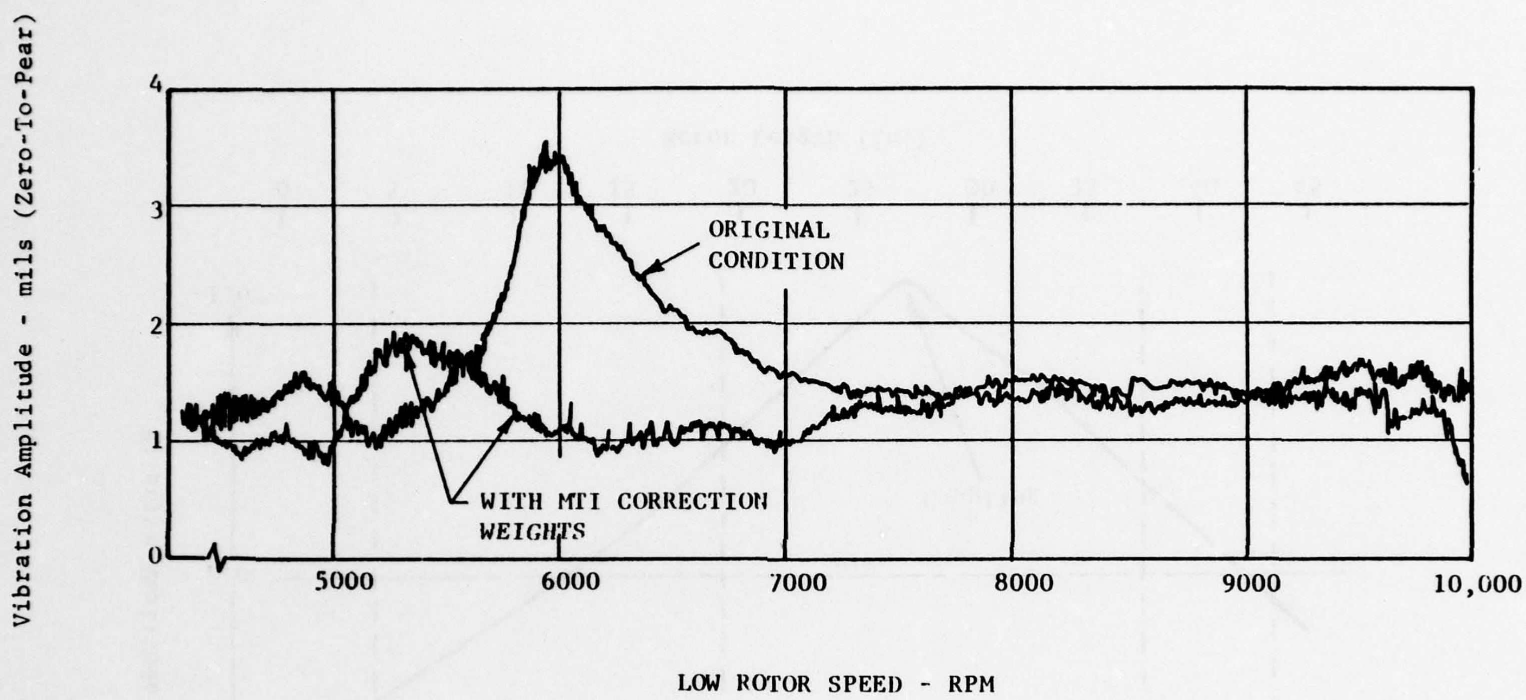


Fig. 13 F100 Vibration Comparison Before and After MTI Correction Weights

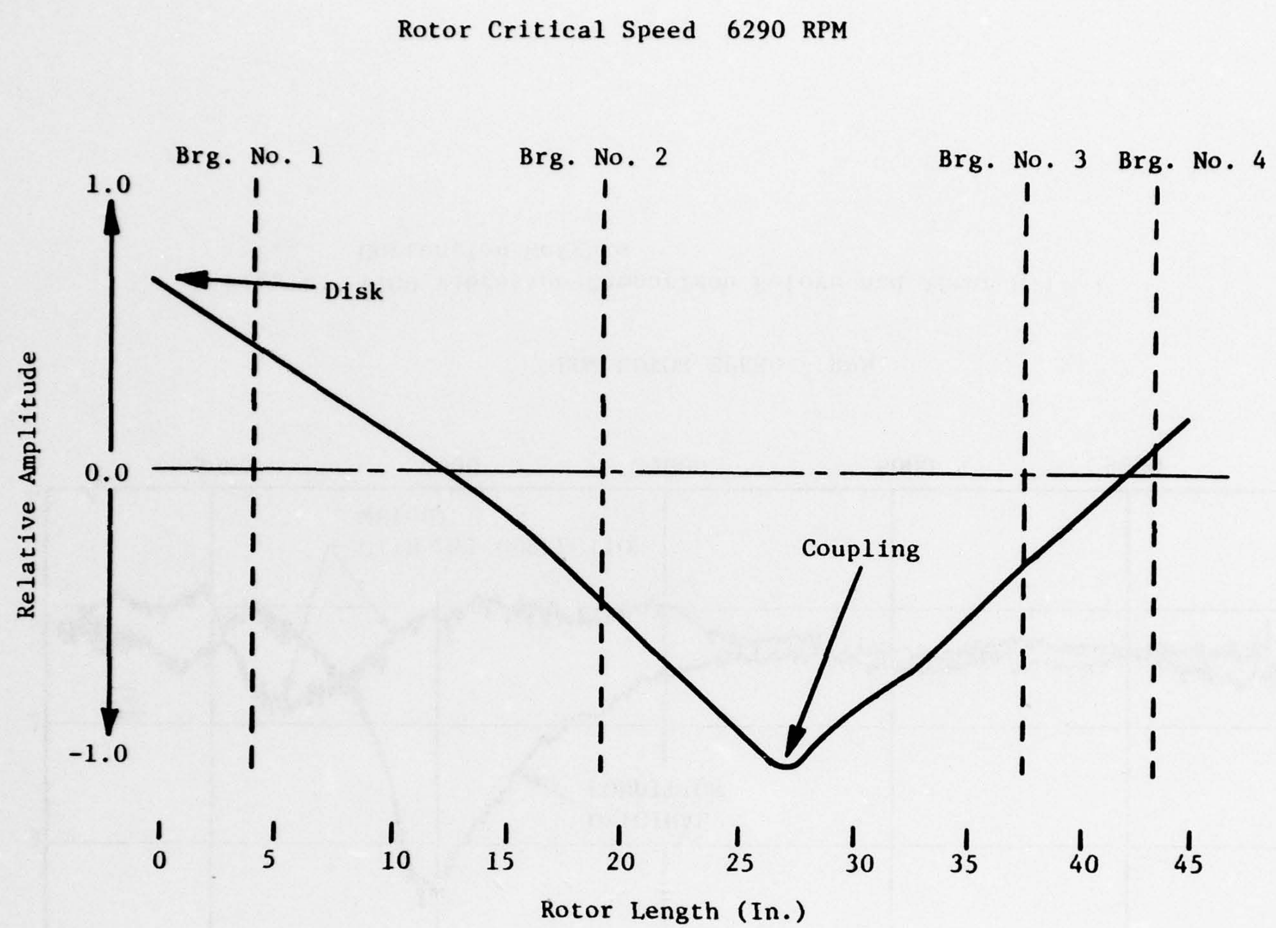


Fig. 14 Mode Shape of Calculated First Critical Speed For Air Force Test Rig

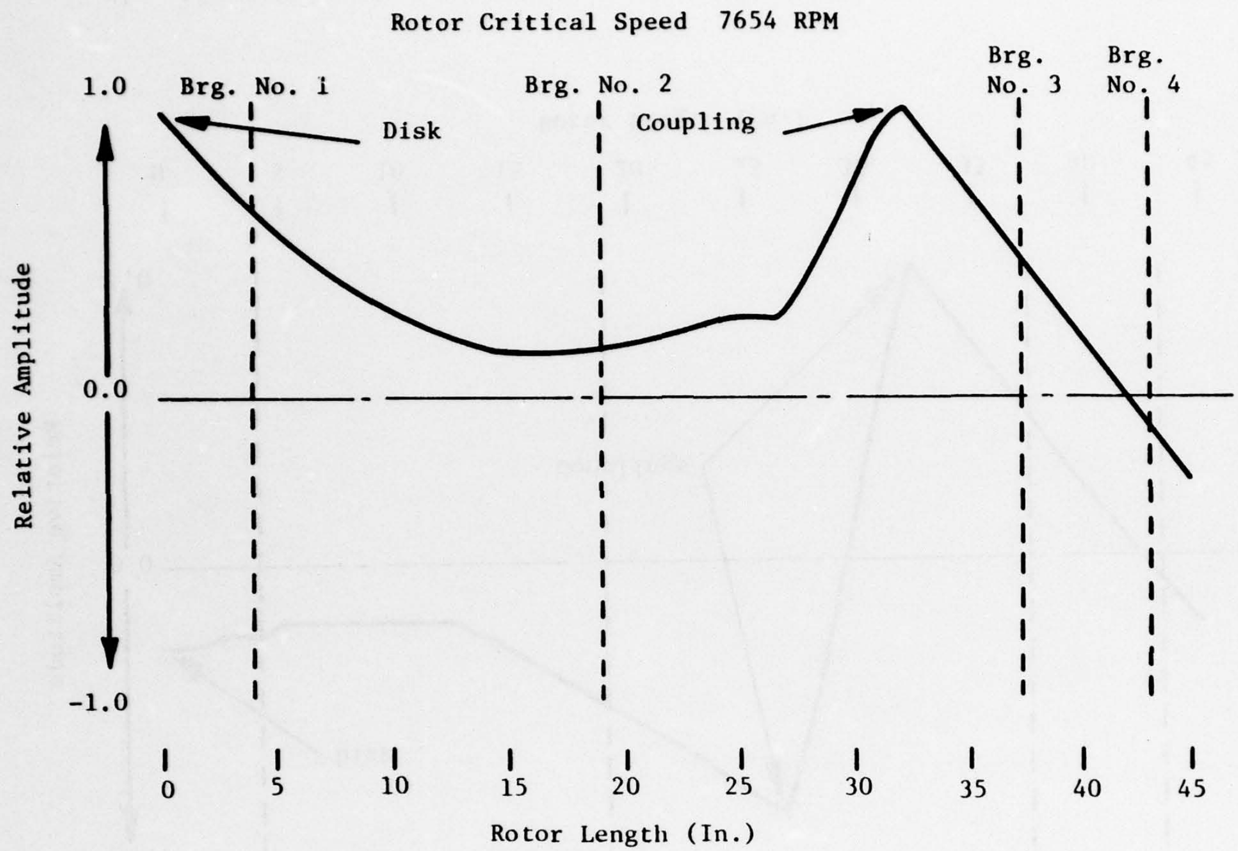


Fig. 15 Mode Shape of Calculated Second Critical Speed for Air Force Test Rig

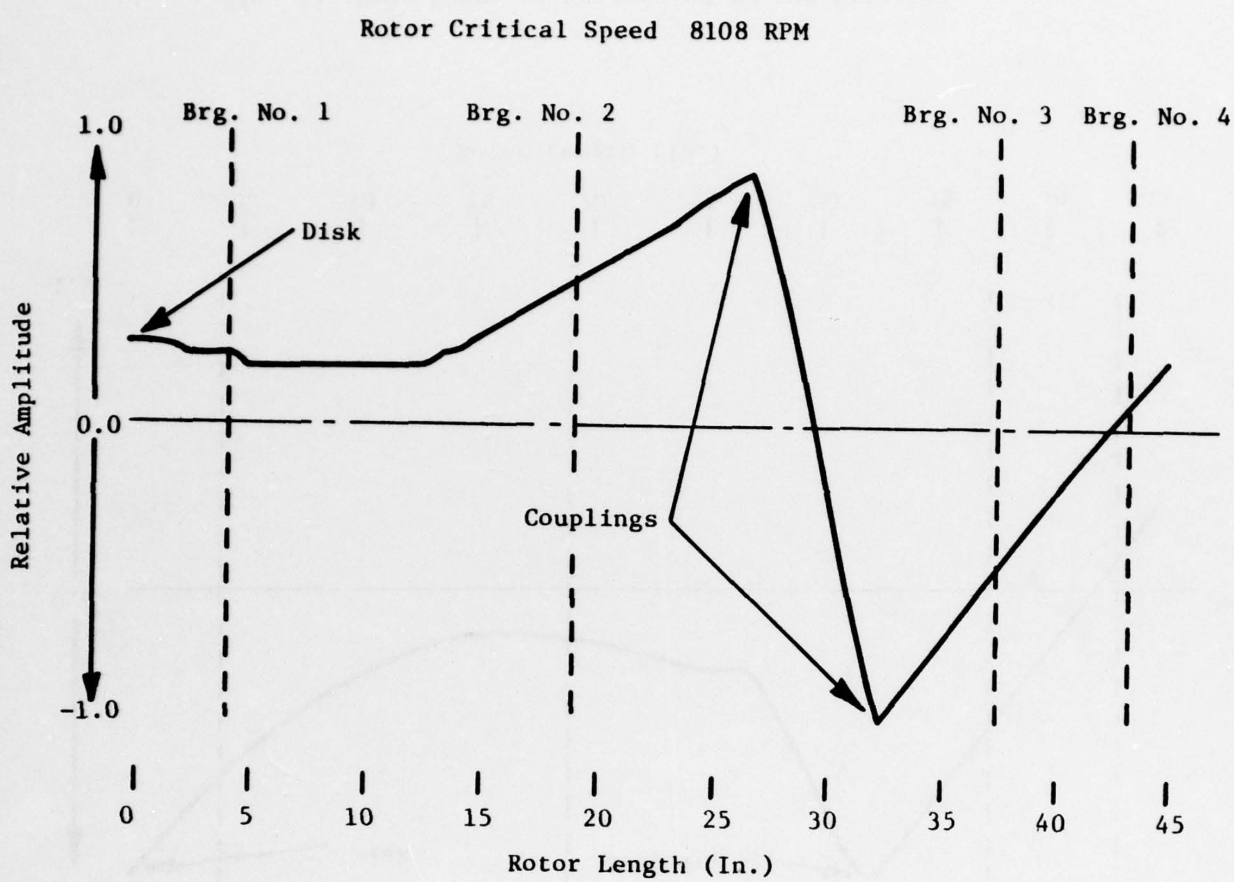


Fig. 16 Mode Shape of Calculated Third Critical Speed Air Force Test Rig

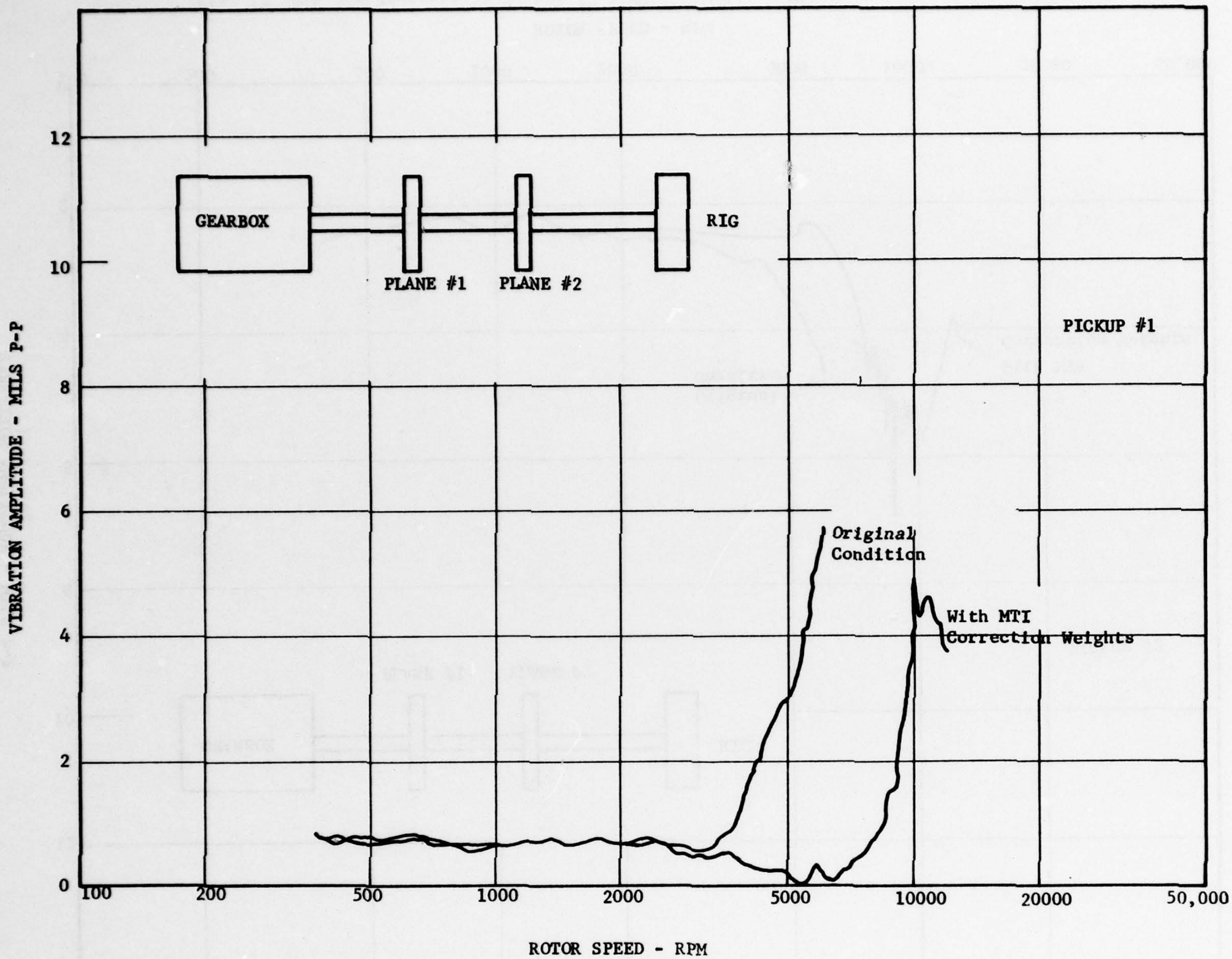


Fig. 17 Rub Rig Response at Pickup #1 Before and After MTI Correction Weights

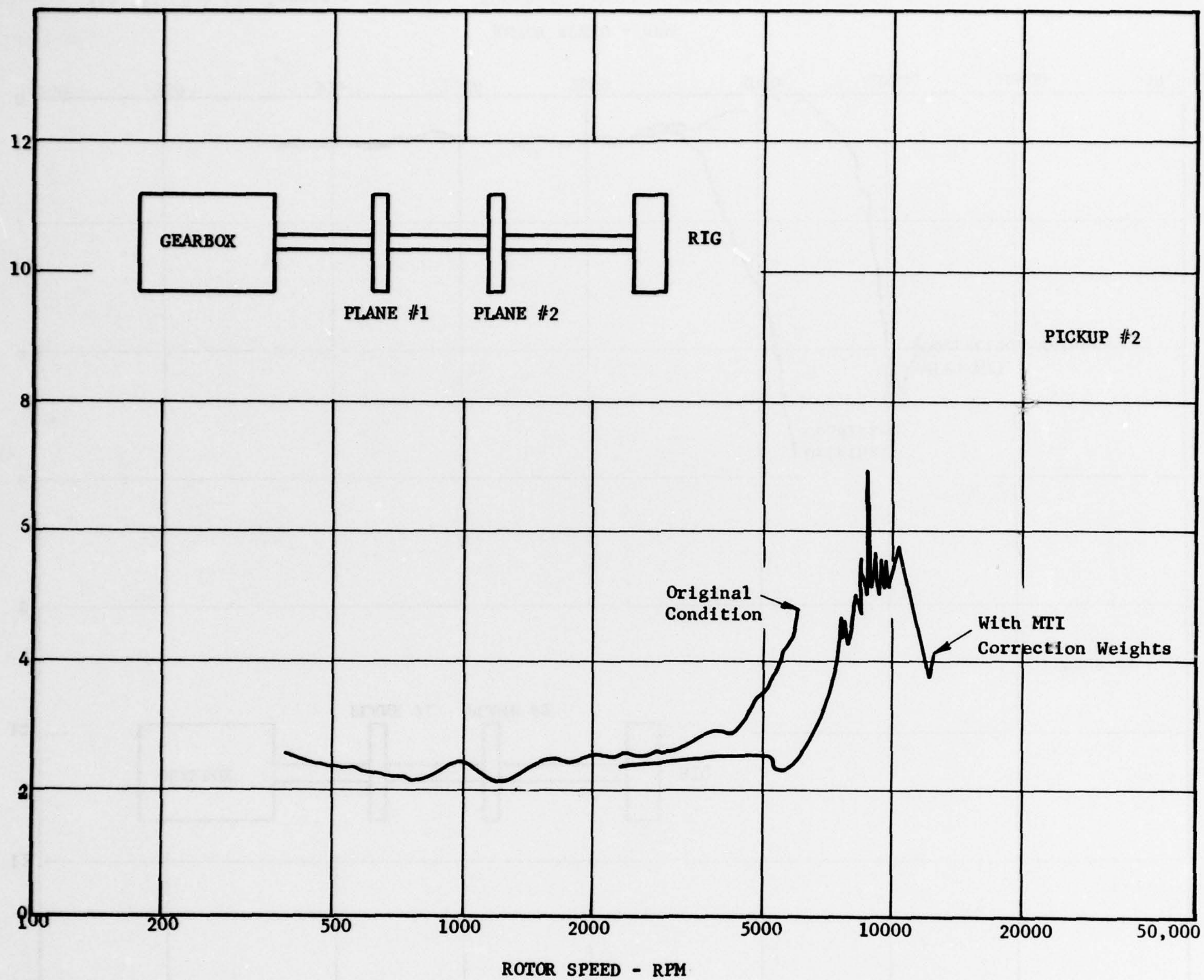


Fig. 18 Rub Rig Response at Pickup #2 Before and After MTI Correction Weights

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